# PROSPECT
## Precision Oscillation and Spectrum Experiment


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*on behalf of the PROSPECT collaboration*

Wright Laboratory

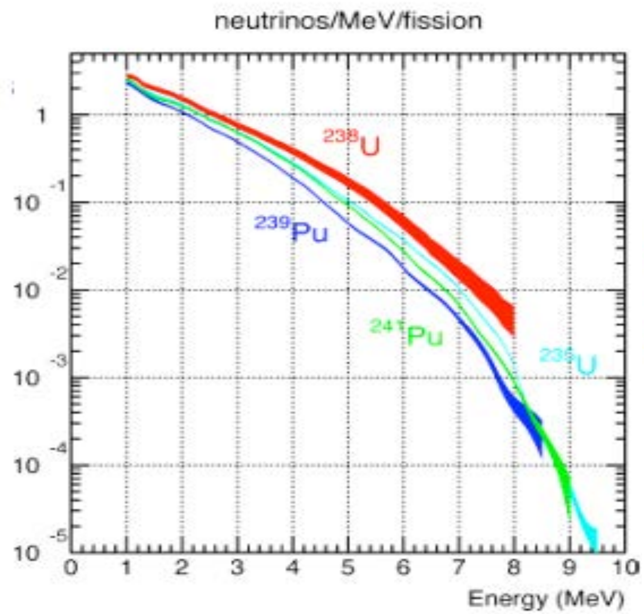
Yale

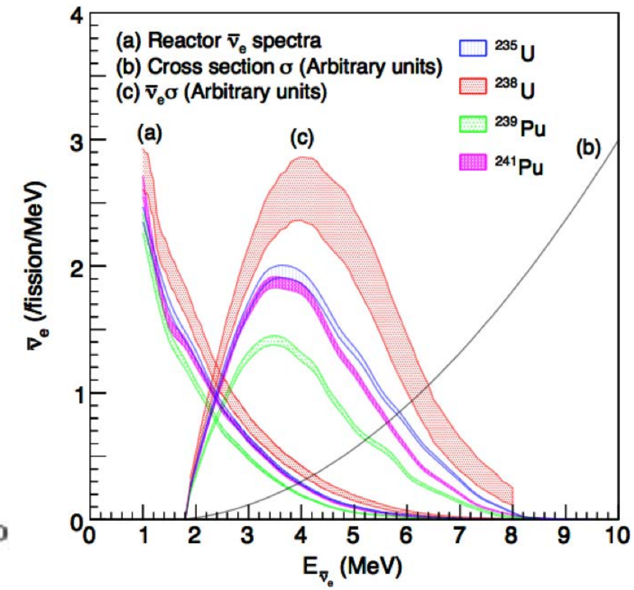
# Reactor Antineutrinos

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

of n-rich fission products

on average ~6 beta decays until stable



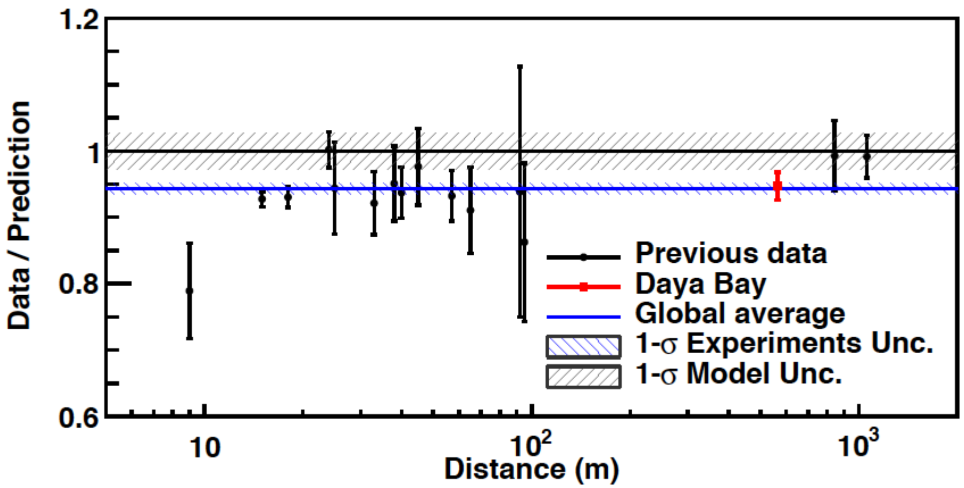

> 99.9% of $\overline{\nu}_e$ are produced by fissions in $^{235}U$, $^{238}U$, $^{239}Pu$, $^{241}Pu$

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

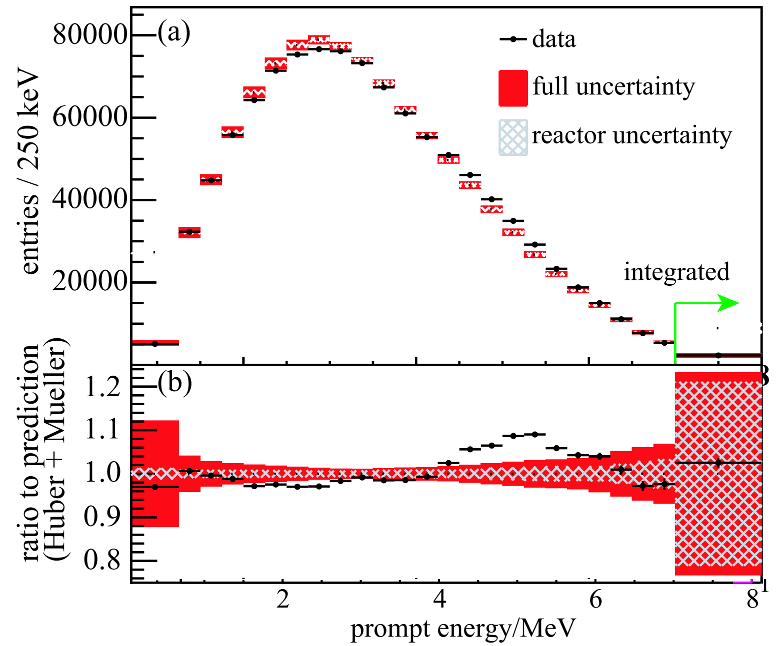
only disappearance experiments possible

# Reactor Antineutrino “Anomalies” (RAA)

## Flux Deficit




## Spectral Deviation




Deficit due to extra (sterile) neutrino oscillations or artifact of flux predictions?

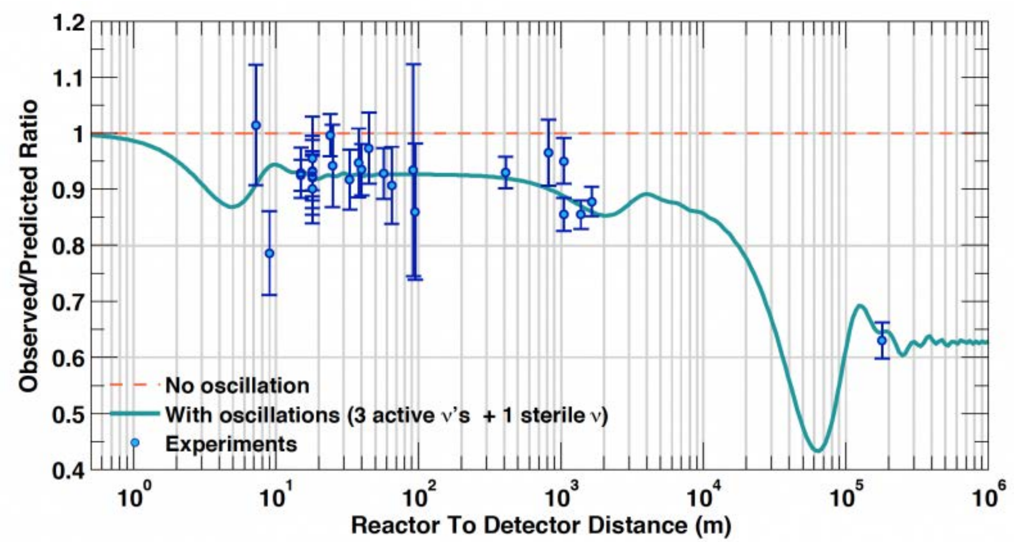
Measured spectrum does not agree with predictions.

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

Understanding reactor flux and spectrum anomalies requires additional data

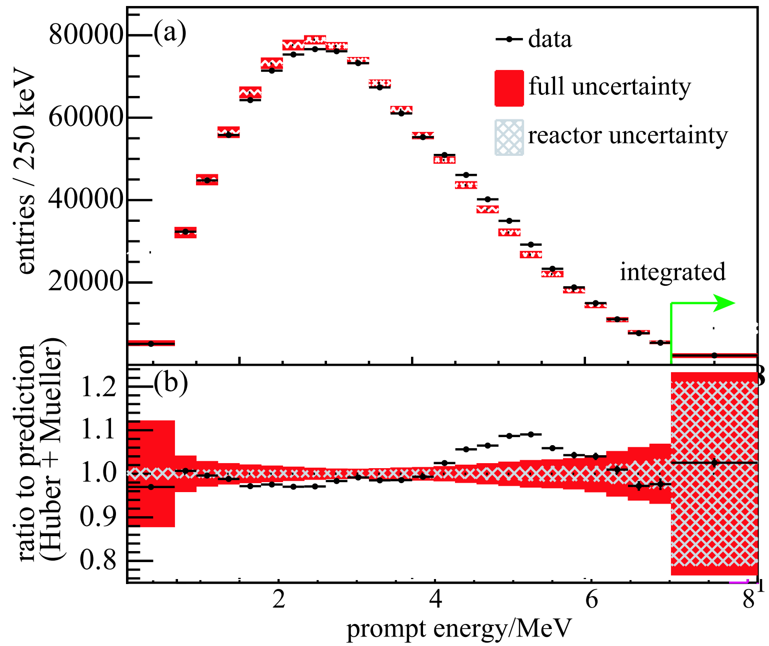
# Reactor Antineutrino “Anomalies” (RAA)

## Flux Deficit




Phys. Rev. D 83, 073006 (2011)

## Spectral Deviation

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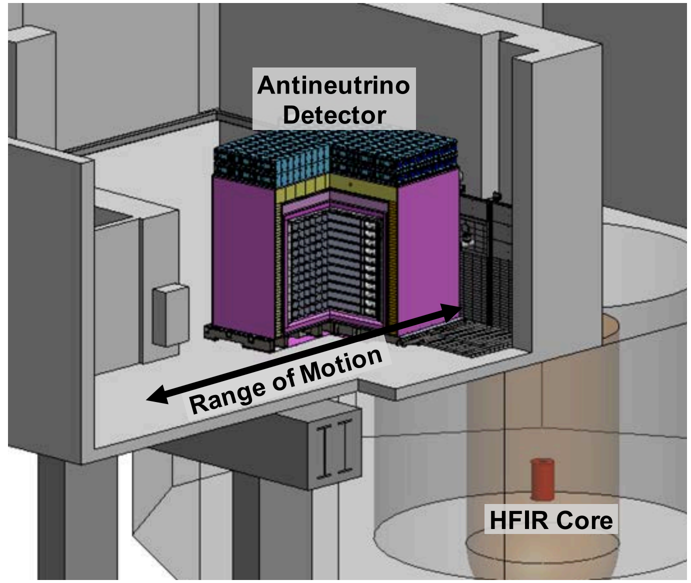
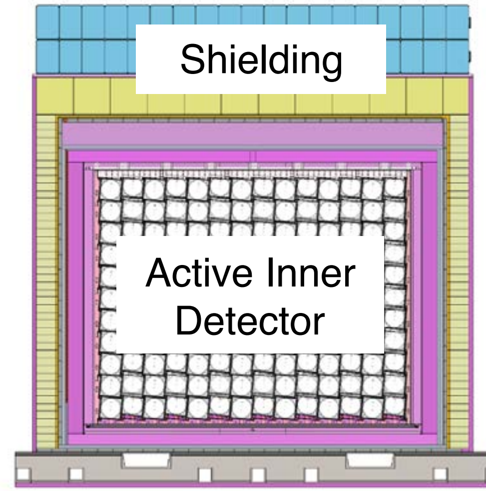
# Precision Oscillation and Spectrum Experiment

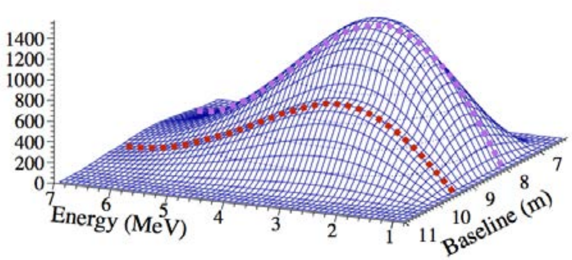




**Objectives** **Search for short-baseline oscillation at <10m**
**Precision measurement of $^{235}$U reactor $\overline{\nu}_e$ spectrum**

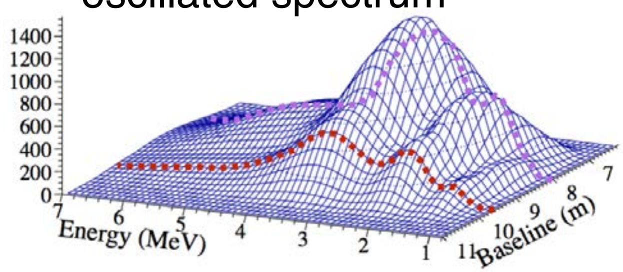
Relative Spectrum Measurement
relative measurement of L/E and spectral shape distortions

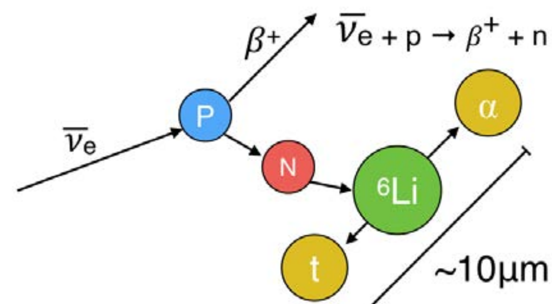
Segmented, $^6$Li-loaded Detector

unoscillated spectrum

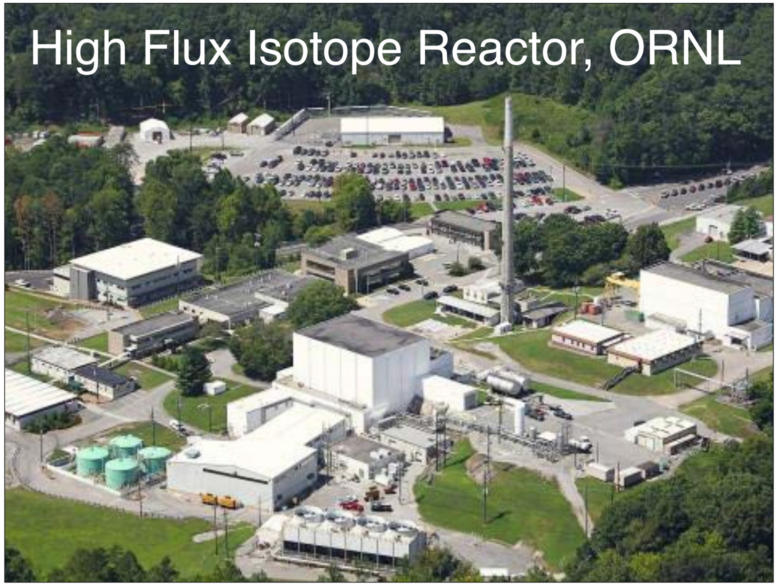



oscillated spectrum



# Experimental Site





## Reactor Core

**Power**: 85 MW
**Core shape:** cylindrical
**Size:** h=0.5m r=0.2m
**Duty-cycle**: 46%, 7 cycles/yr, 24 days
**Fuel:** HEU ($^{235}$U)

**compact reactor core, detector near surface, little overburden**

highly-enriched (HEU): >99% of $\overline{\nu}_e$ flux from $^{235}$U fission

# PROSPECT Detector Design

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)

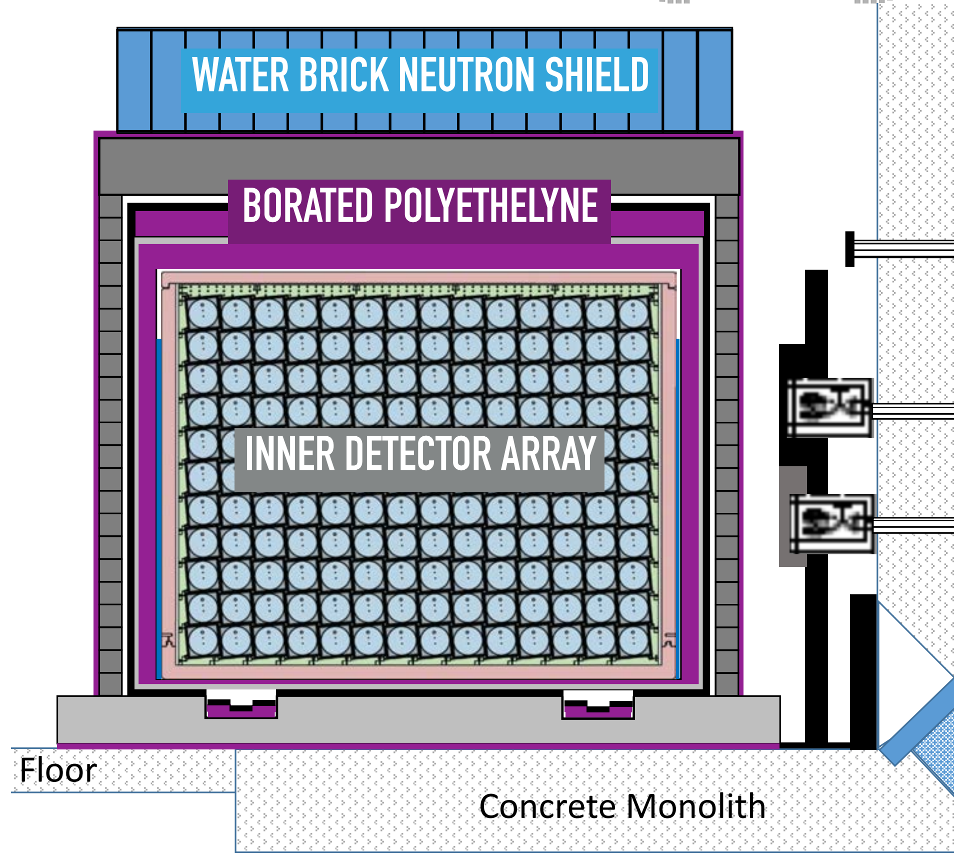
Corner support rods allow for full *in situ* calibration access

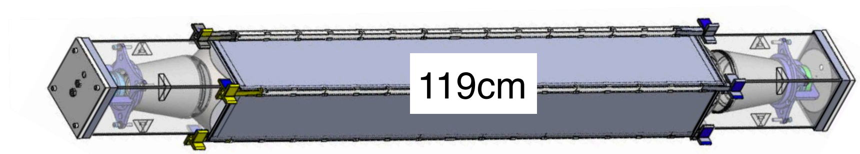
**Double ended PMT readout,** with light concentrators

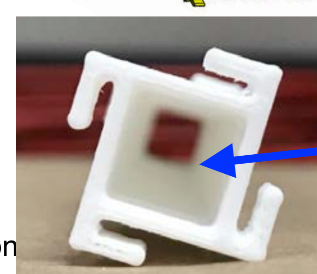
good light collection and energy response ~4.5-5%√E energy resolution

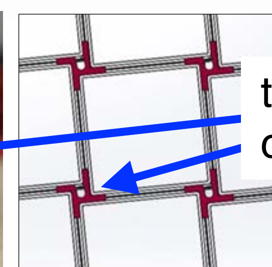
full X,Y,Z event reconstruction

**Optimized shielding to reduce cosmogenic backgrounds**



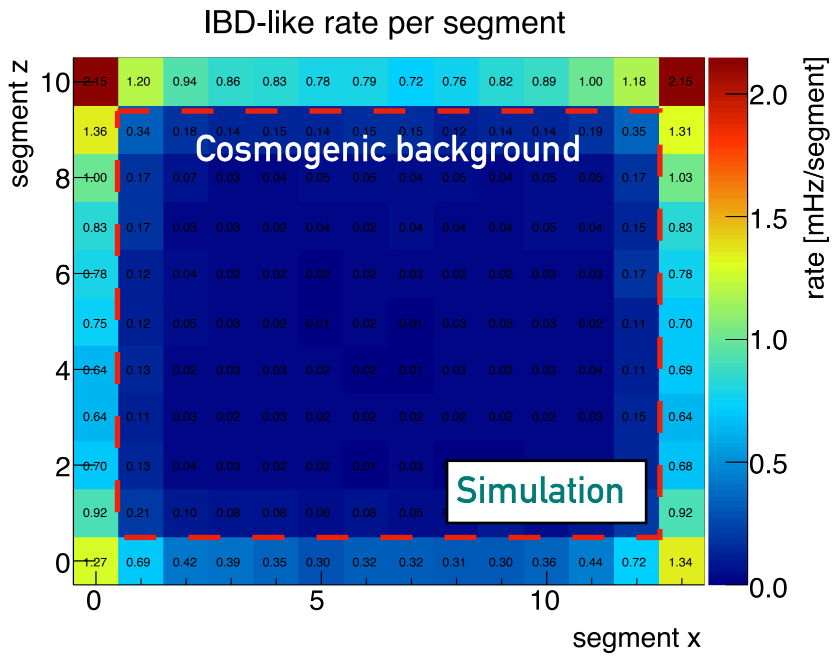



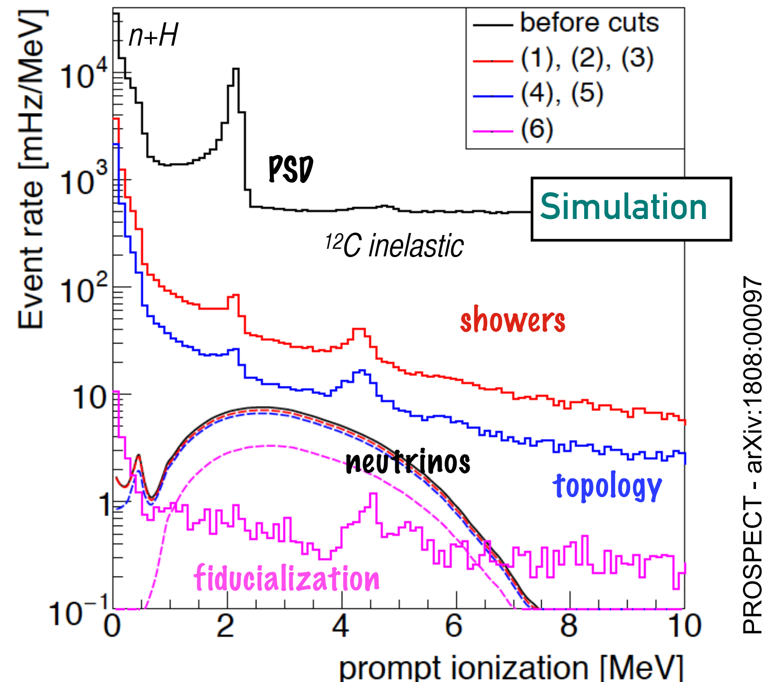





tilted array for calibration access

# 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

# Assembly of First Row
# November 1, 2017

[Assembly in 30s (video)]

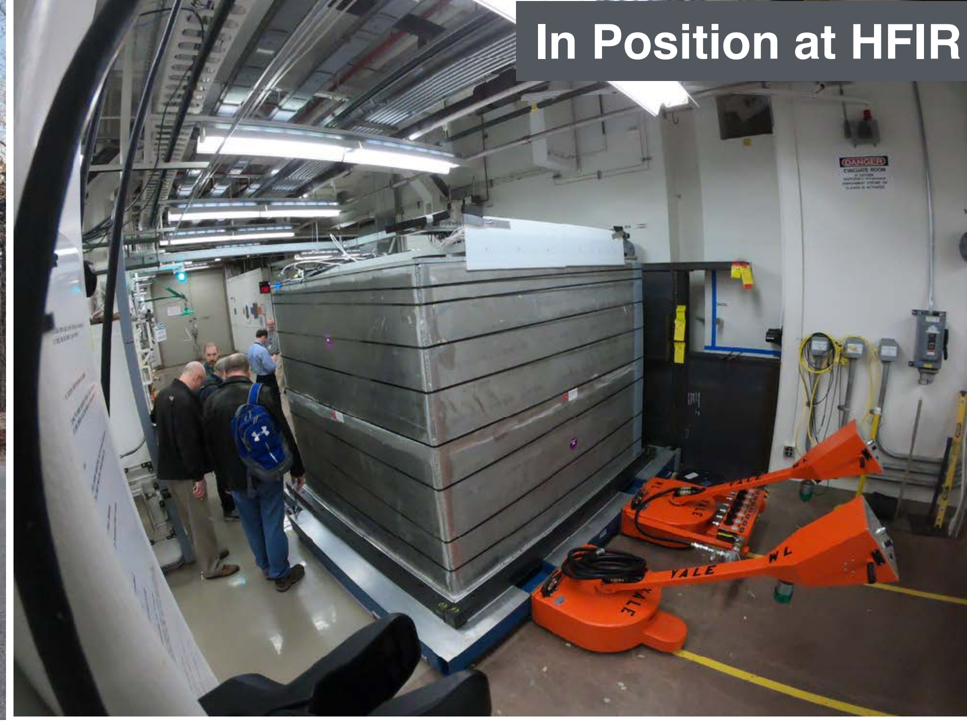
Wright Laboratory

# Final Row Installation November 17, 2017

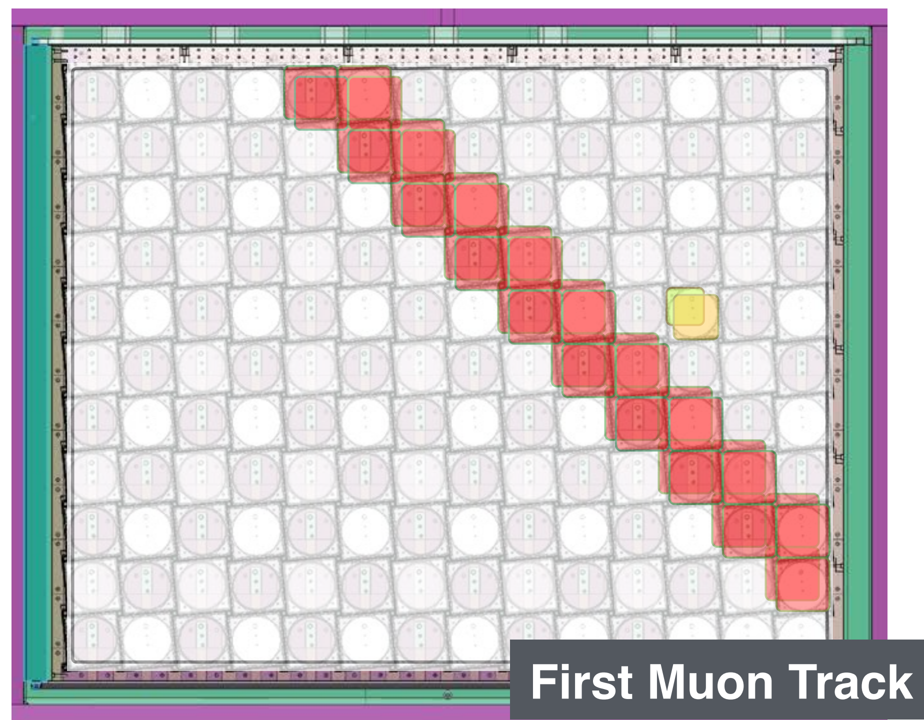
Wright Laboratory


Dry Commissioning
Dec 2017 - Jan 2018
Wright Laboratory

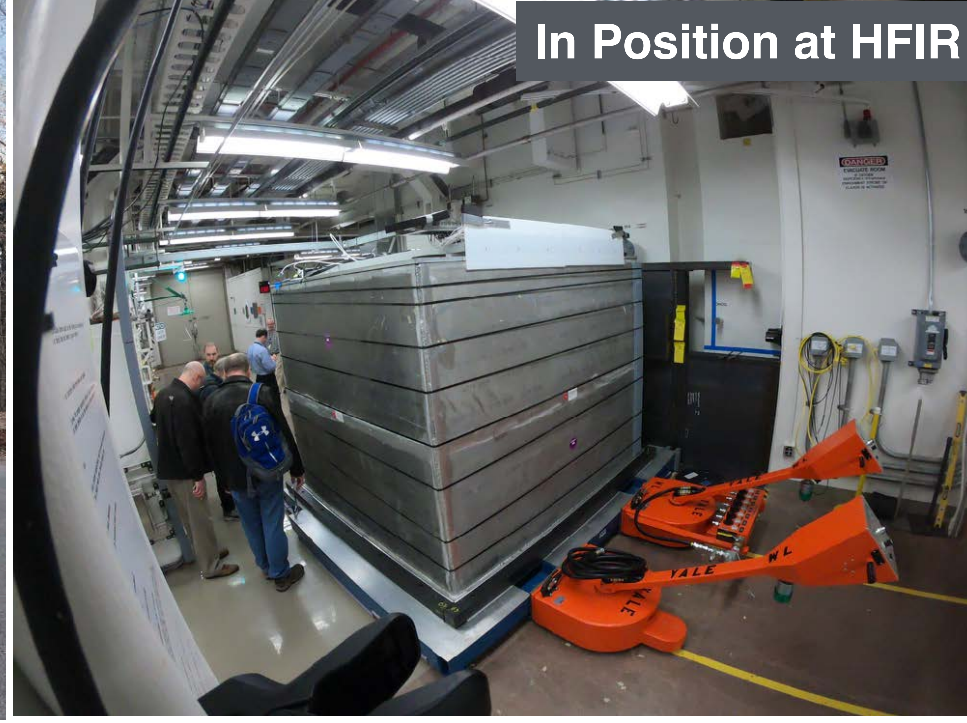

February 2018
Arrival at ORNL


In Position at HFIR


Filling from Mixing Tank


First Muon Track


February 2018
Arrival at ORNL

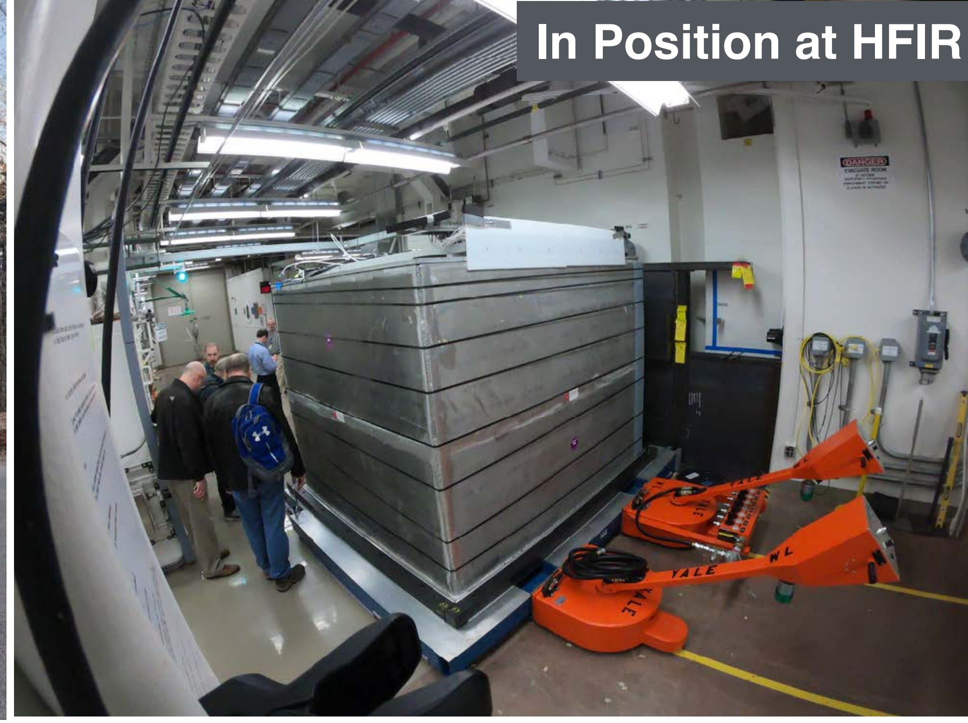


In Position at HFIR

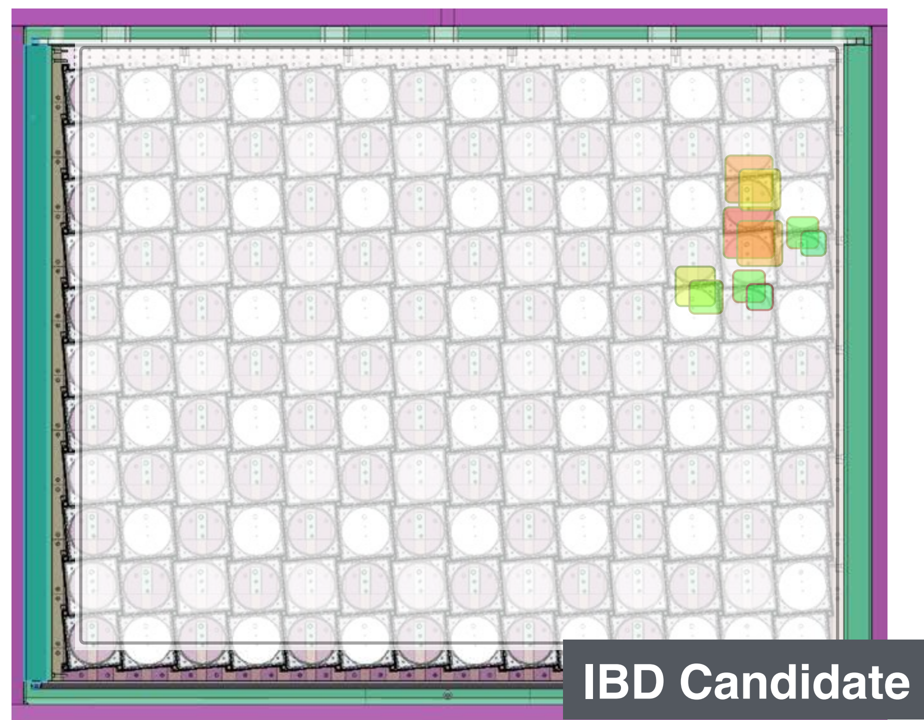
Filling from Mixing Tank


Hadronic Shower


February 2018
Arrival at ORNL


In Position at HFIR
YALE

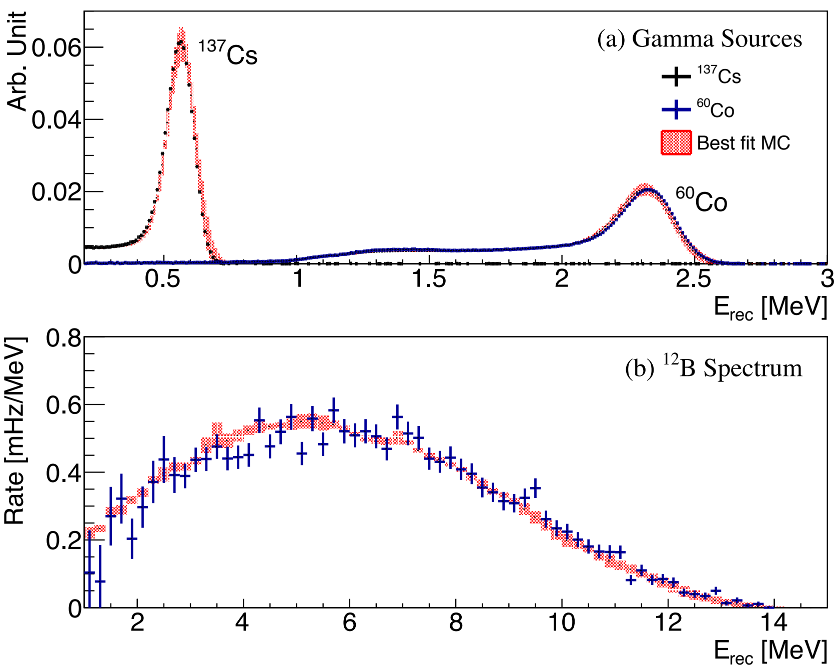

TARE
DANGER
NOMINAL CAPACITY
Filling from Mixing Tank


IBD Candidate

# Energy Reconstruction

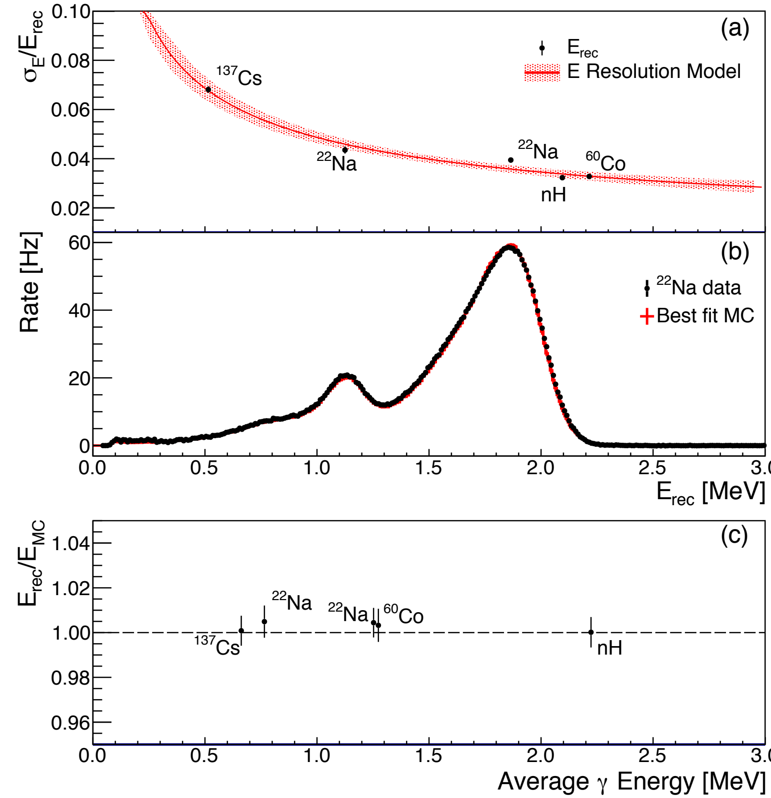
**Gamma sources** ($^{137}$Cs, $^{60}$Co, $^{22}$Na) deployed throughout detector, measure single segment response

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




Phys.Rev.Lett. 121 (2018) no.25, 251802
PROSPECT Collaboration

## Resolution and Reconstruction




E[MeV]

MC/data for calibration peaks agrees to better than 1σ

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

High light collection: 795±15 PE/MeV

# First Oscillation Analysis Data Set

33 days of Reactor On

28 days of Reactor Off

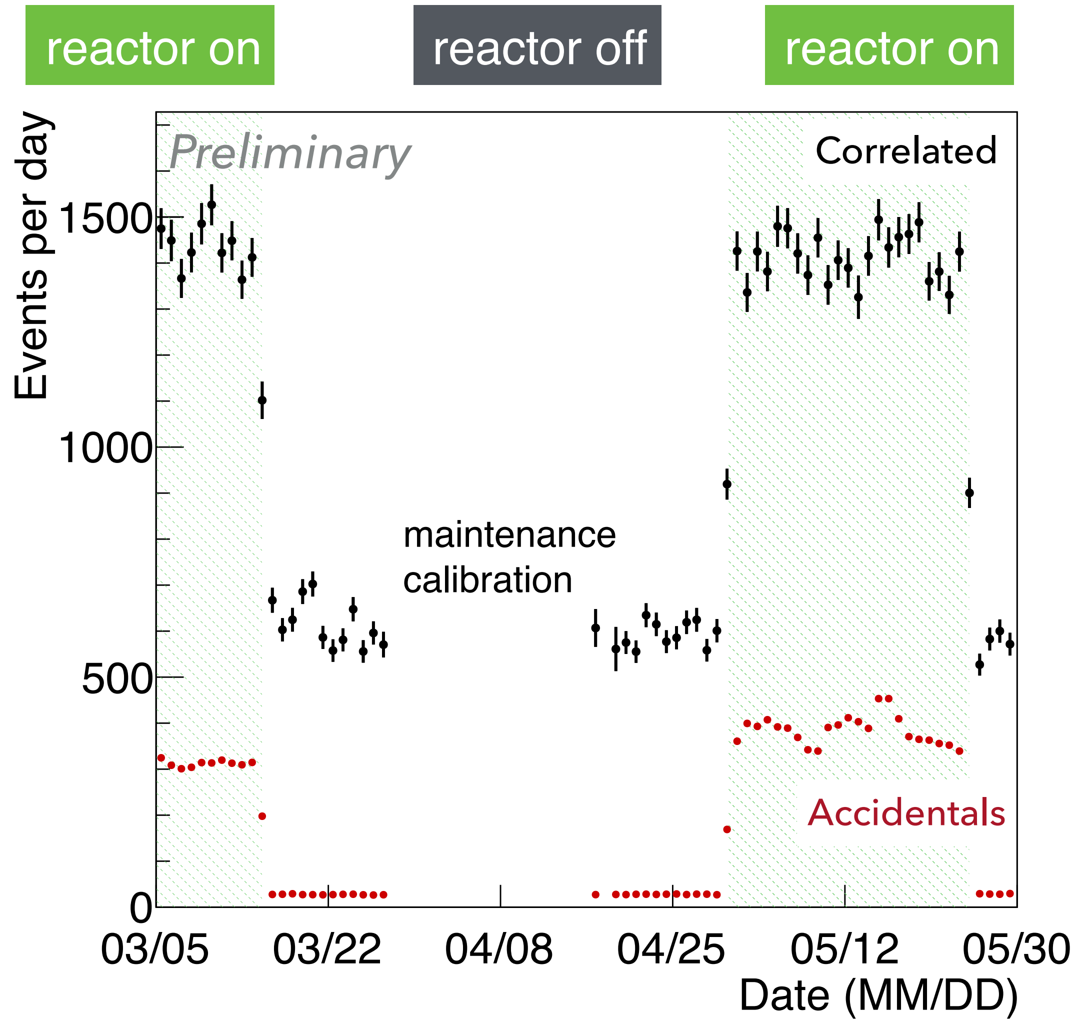
Correlated S/B = 1.36

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

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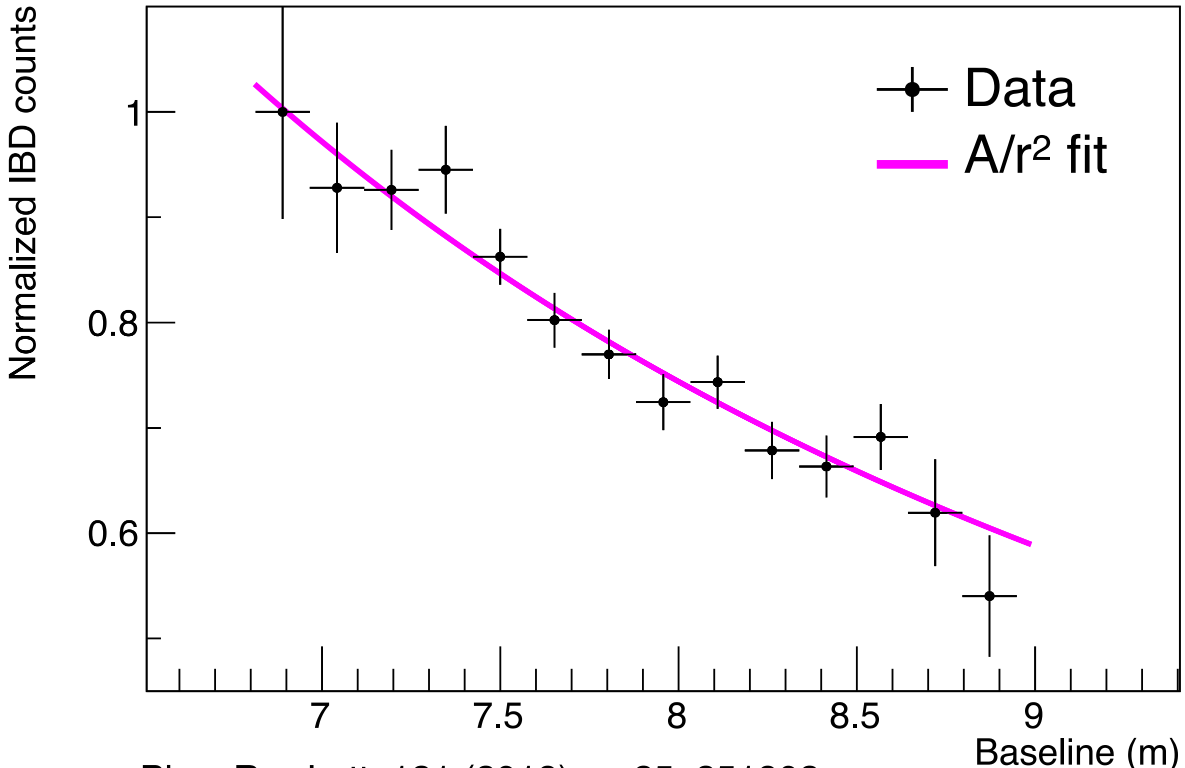
# Neutrino Rate vs Baseline

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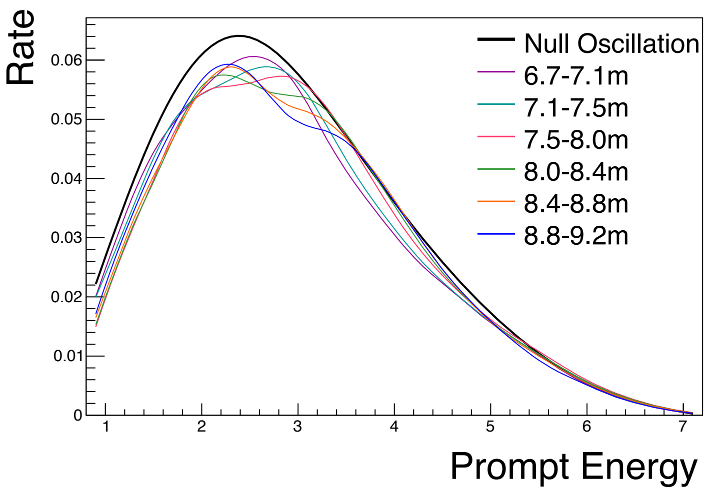
Observation of $1/r^2$ behavior throughout detector volume

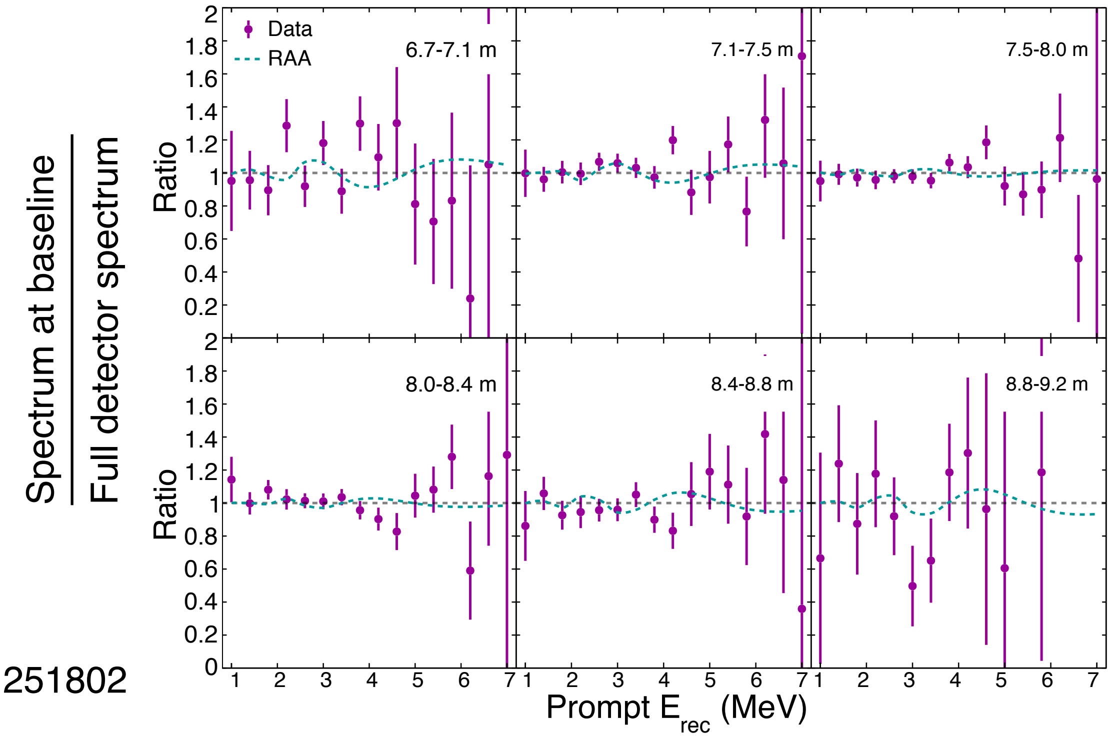
Bin events from 108 fiducial segments into 14 baseline bins

*40% flux decrease from front of detector to back*

# Neutrino Spectrum vs Baseline

## Spectral Distortion vs Baseline

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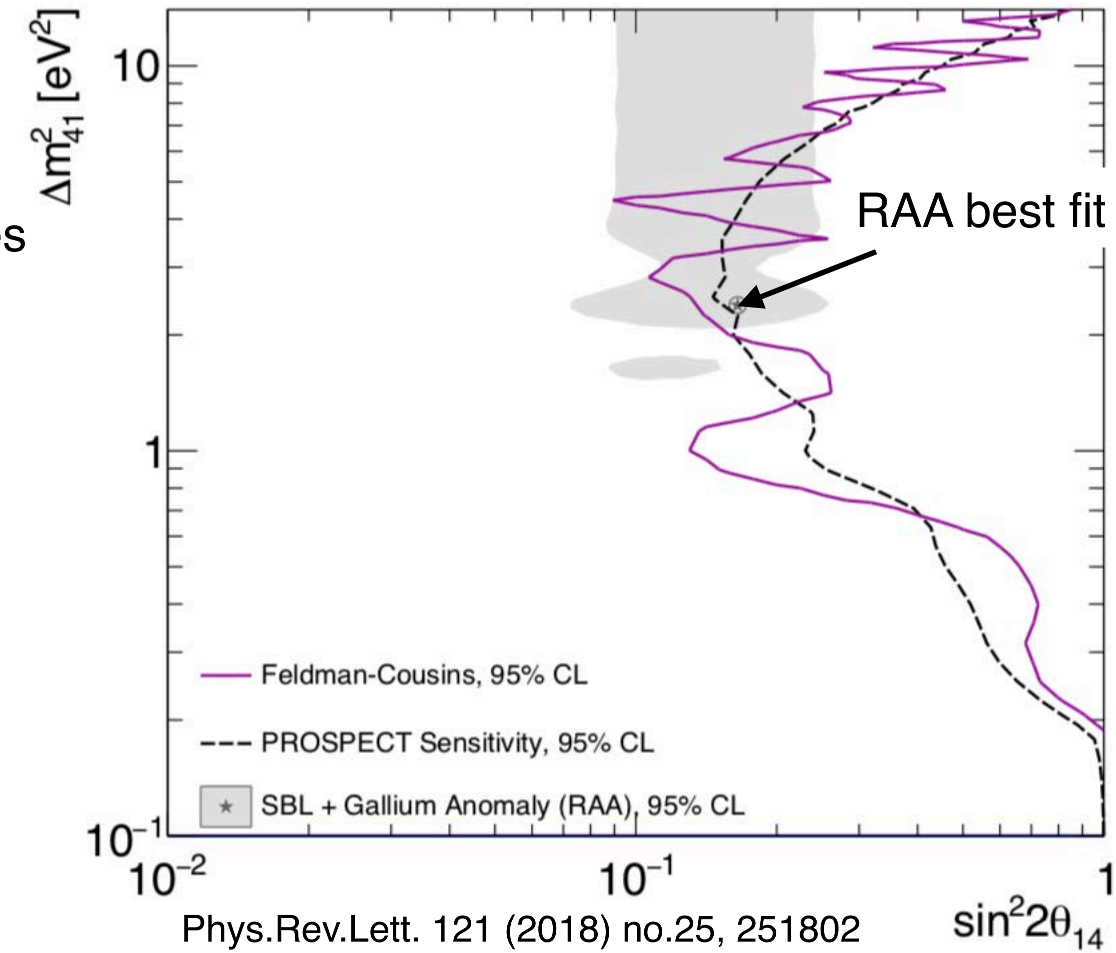
Compare spectra from 6 baselines to measured full-detector spectrum

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 $\chi^2$ 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**

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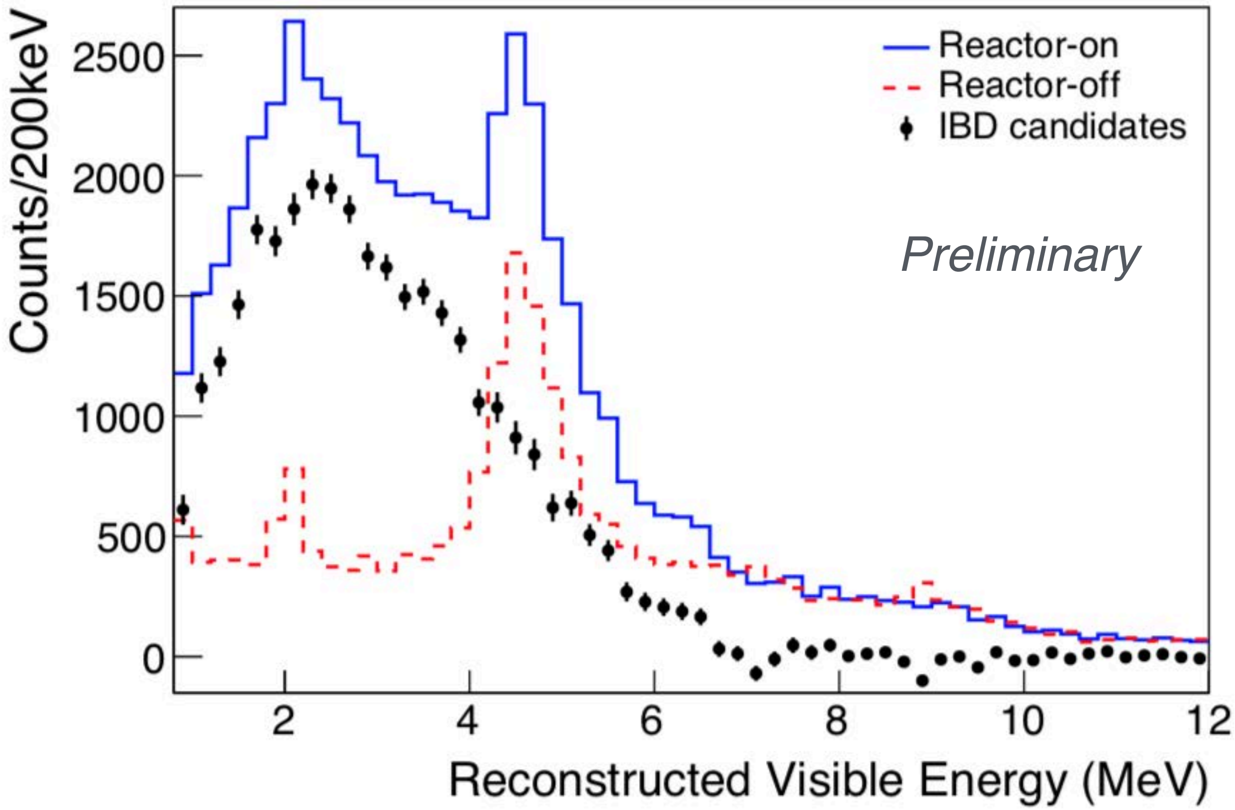
**Disfavors RAA best-fit point at >95% CL (2.2$\sigma$)**

# New Measurement of $^{235}U$ Spectrum

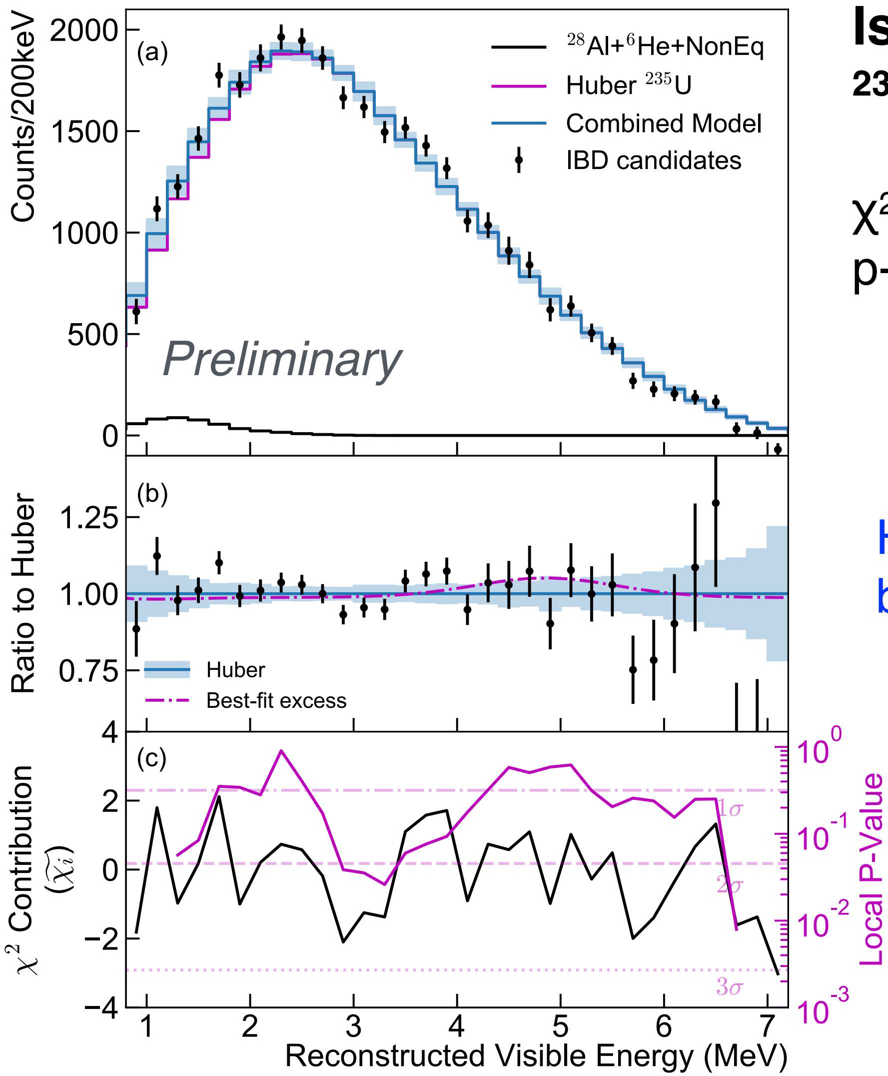
Prompt Energy Spectrum




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

measured spectrum with good S/B at surface 1.7/1 (0.8-7.2 MeV)
~ 6x greater statistics than ILL (1981)

# Prompt Energy Spectrum



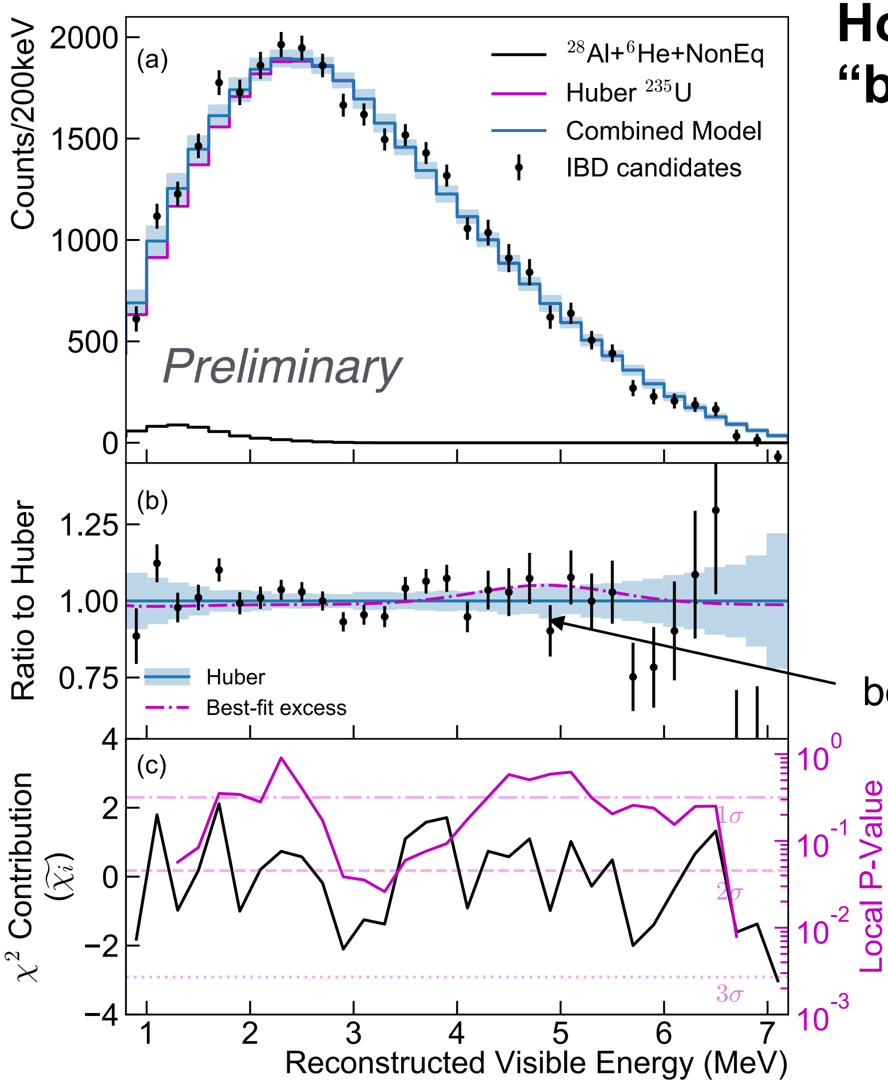

## Is PROSPECT consistent with Huber $^{235}$U model for HFIR HEU reactor?

$\chi^2$/ndf = 52.1/31
p-value = 0.01

Huber model broadly agrees with spectrum but is not a good fit.

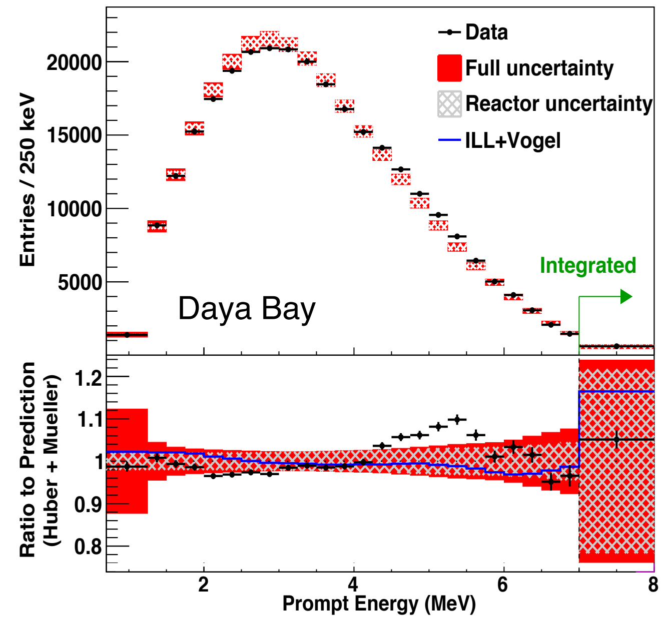
Deviations mostly in two energy regions.

# Prompt Energy Spectrum




best-fit excess

## How does PROSPECT compare to "bump" in $\theta_{13}$ experiments?




Shape of measured $^{235}$U spectrum not inconsistent with the deviation relative to prediction observed at LEU reactors.

# Summary

PROSPECT started taking data on March 6, 2018

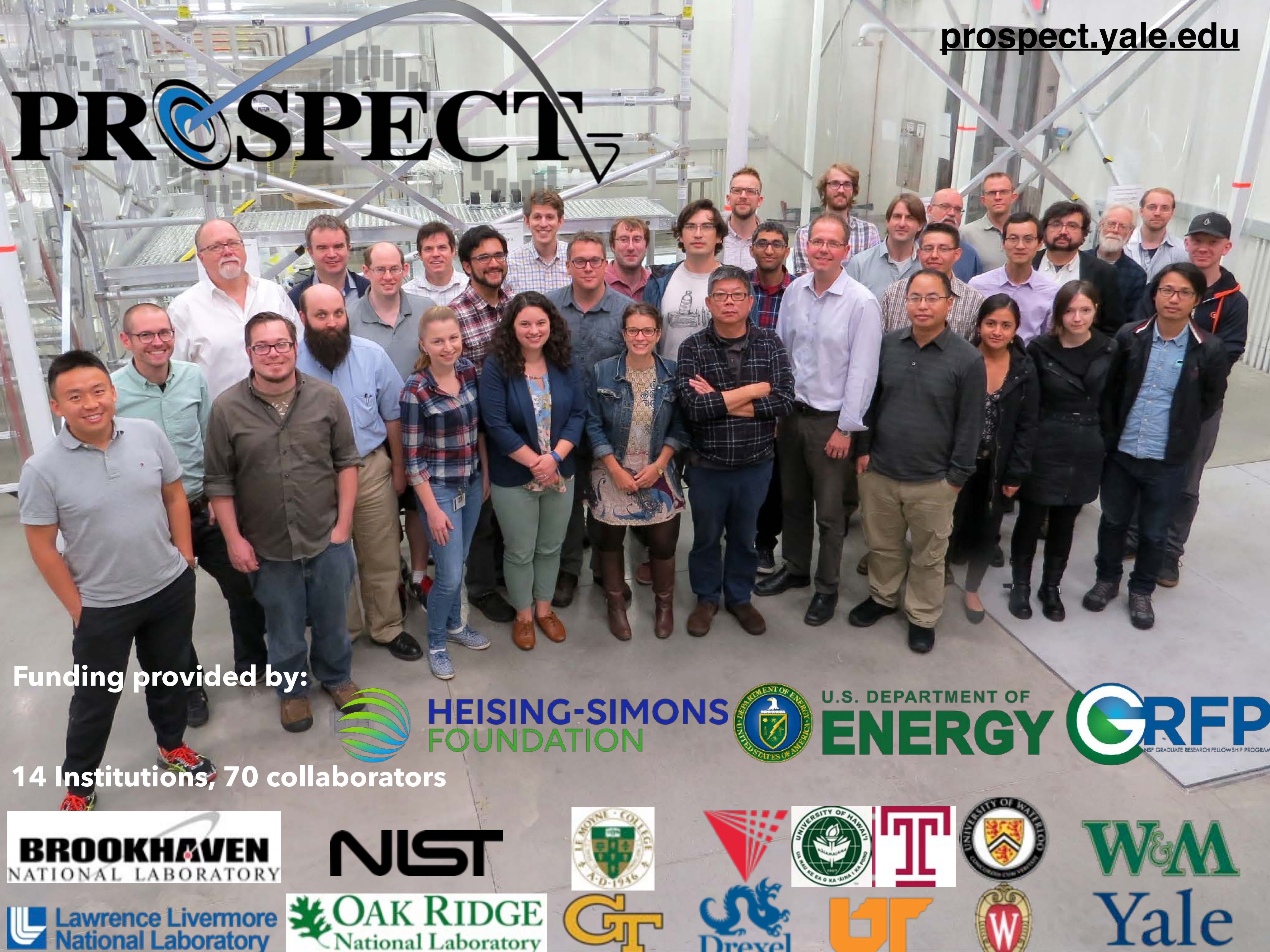
Background rejection and energy resolution meet expectation and match Monte Carlo.

**World-leading signal-to-background for a surface-based detector (<1 mwe overburden).** Observed antineutrinos from HFIR with good signal/background.

**First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.2$\sigma$.**

**Made first modern measurement of an antineutrino spectrum from a HEU reactor with a surface-based experiment.**

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