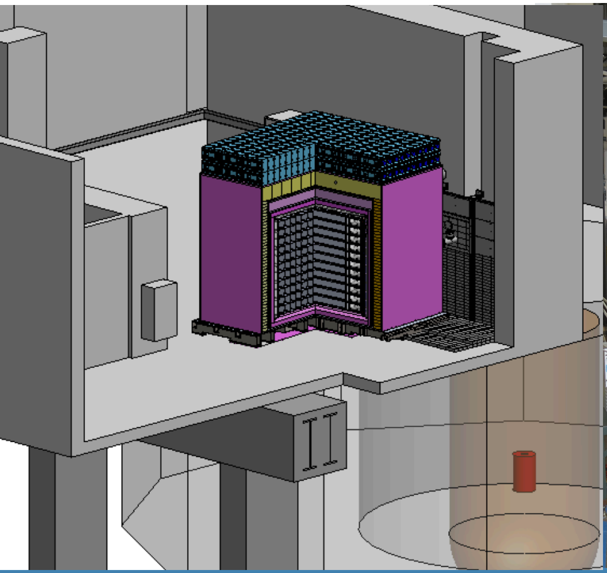
A Precision Oscillation and Spectrum Experiment

Nathaniel Bowden
For the PROSPECT collaboration

PANIC 2017

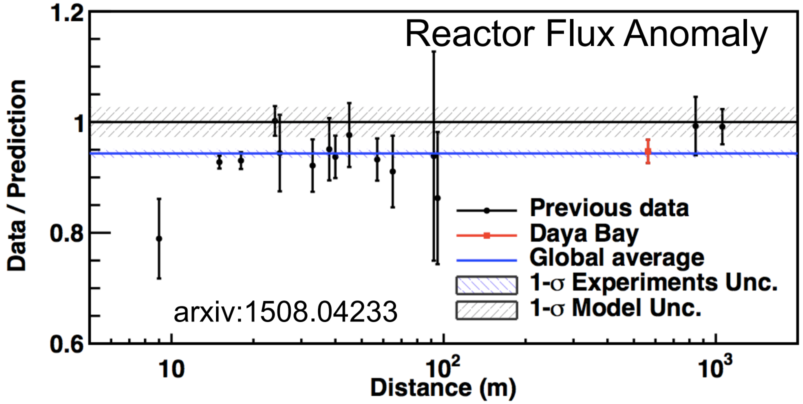


LLNL-PRES-737668
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

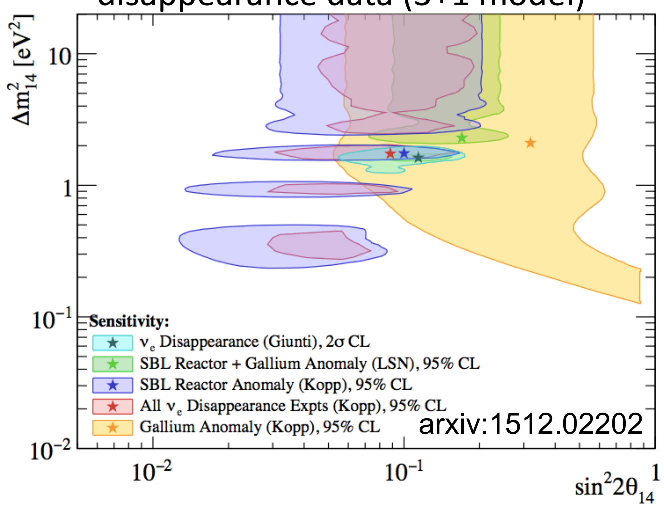
Lawrence Livermore National Laboratory

Motivation

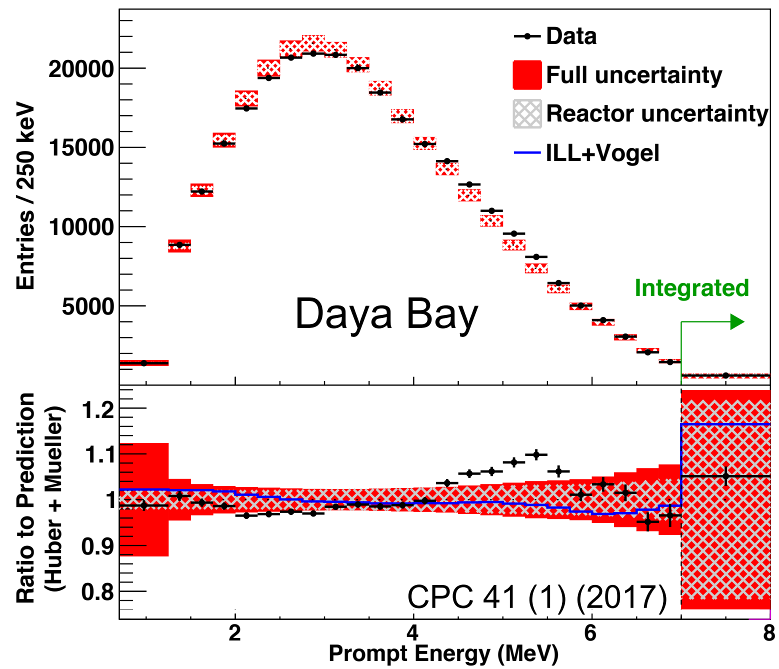
Directly test the hypothesis of a new oscillation with $\Delta m^2 \sim 1\ eV^2$, i.e. oscillation length of few meters



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



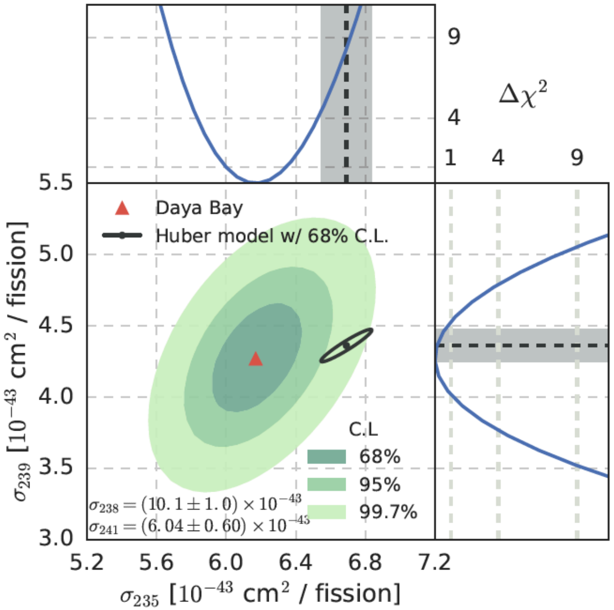
Provide new tests of reactor models by making precision measurements of novel reactor spectra, esp. ^{235}U fuel



Recent Developments: Flux evolution & IBD Yields

Daya Reactor Flux Evolution

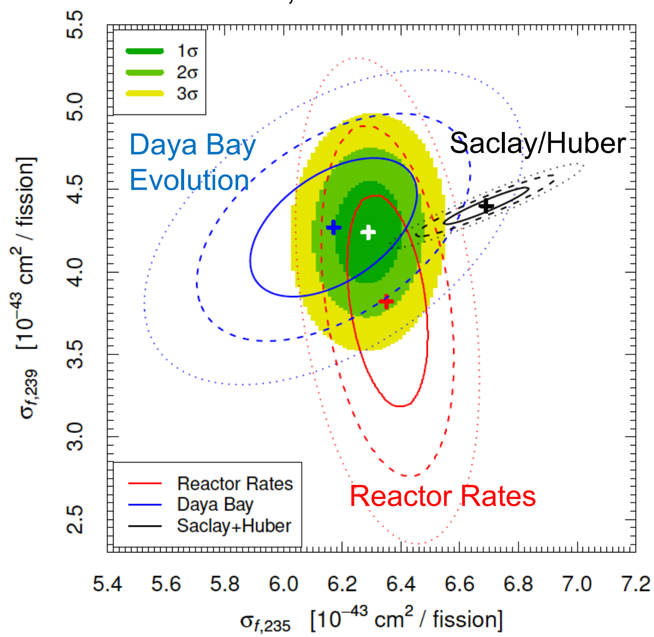
Daya Bay, PRL 118 251801 (2017)



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"

Giunti et al, arXiv:1708.01133

Approach to Short Baseline Reactor Measurements

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

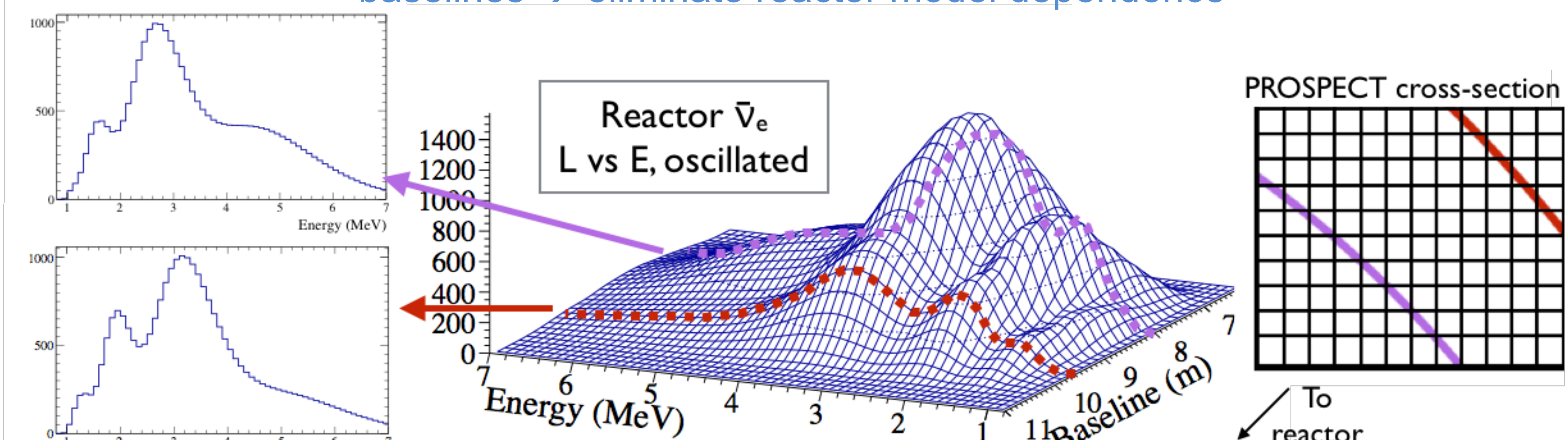


Figure from B. Littlejohn

Research reactors are *generally* preferable:

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

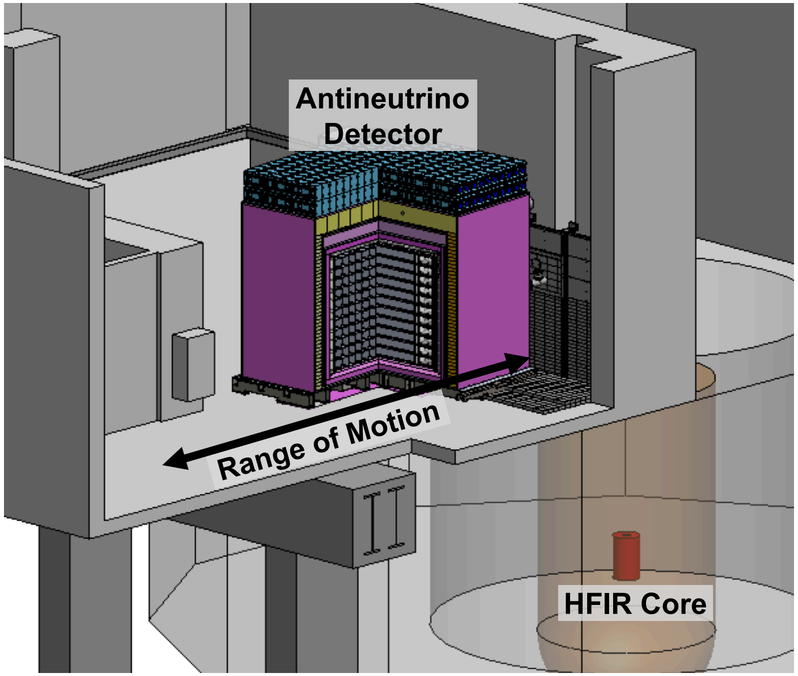
But:

- Limited space for deployment
- Limited overburden
- Possibility of reactor generated background

PROSPECT Experiment Overview

Physics Objectives

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



PROSPECT AD

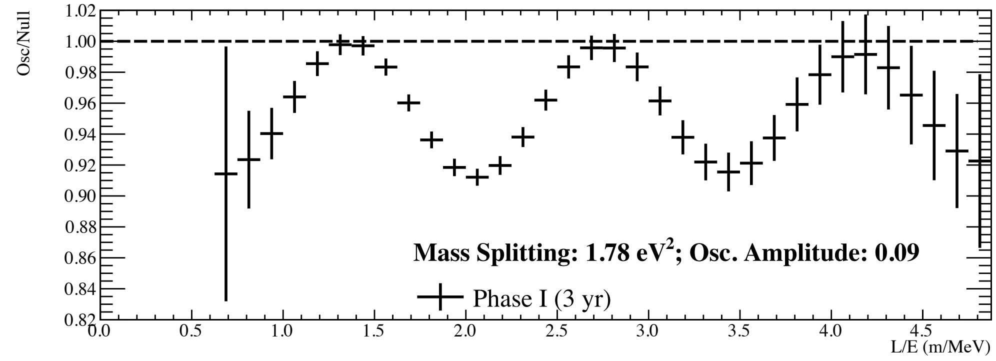
- Segmented design using ^{6}Li-doped liquid scintillator provides strong near-surface background rejection
- movable detector (7-12m baseline range) enables systematic control, background checks, and increased physics reach

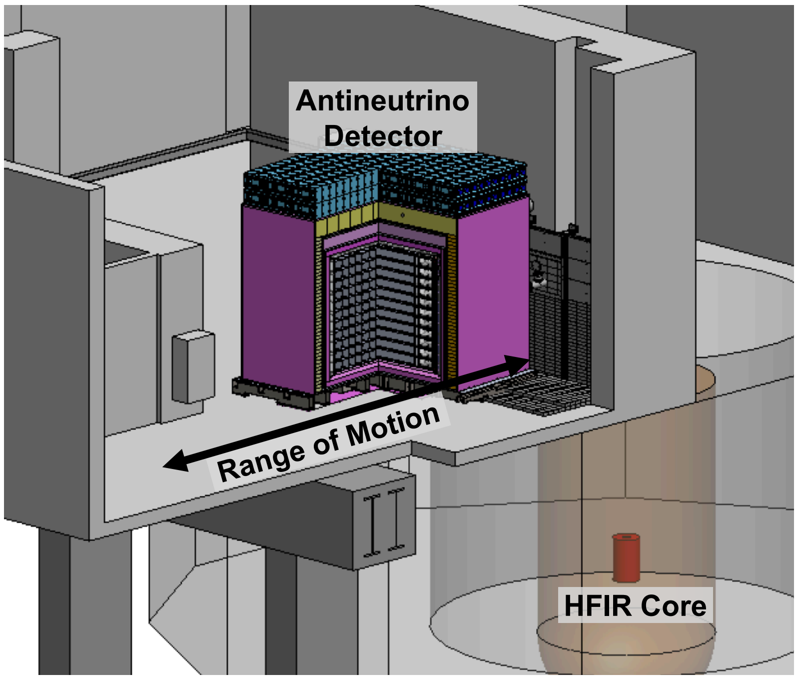
Whitepaper, arXiv:1309.7647
PROSPECT collaboration

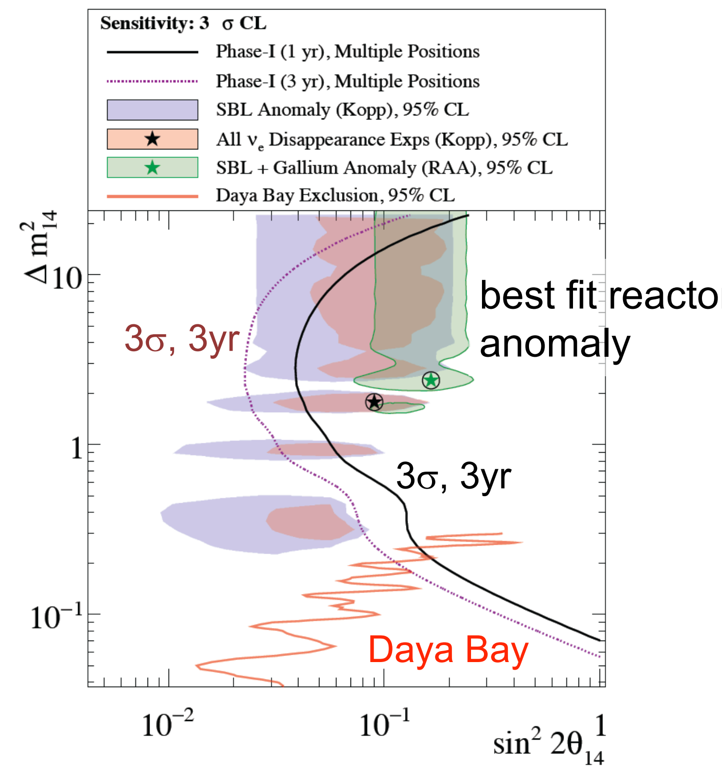
PROSPECT Physics Program
J. Phys. G, 43 113001; arXiv:1512.02202
PROSPECT collaboration

PROSPECT Physics - Precision Oscillation Experiment

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







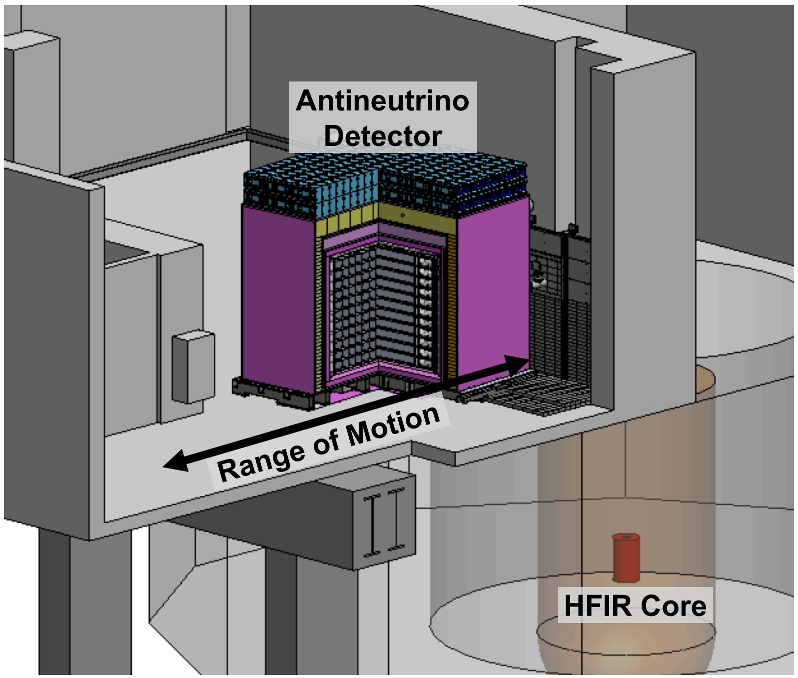
Objectives

4σ test of best fit after 1 year

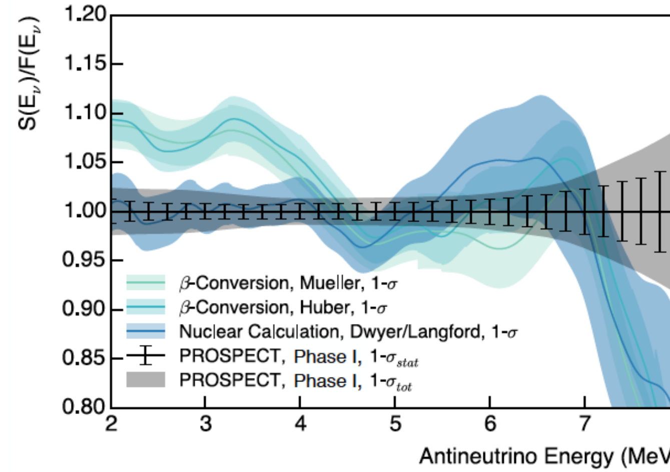
>3σ test of favored region after 3 years

PROSPECT Physics - Precision Spectrum Experiment

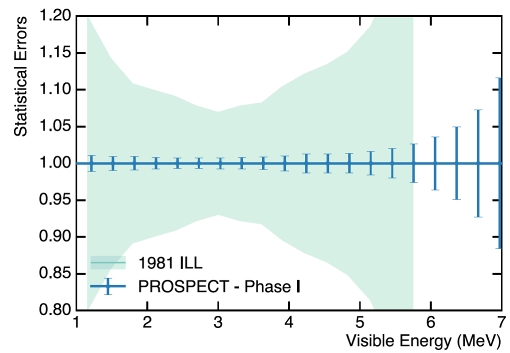
A precision measurement to address spectral unknowns



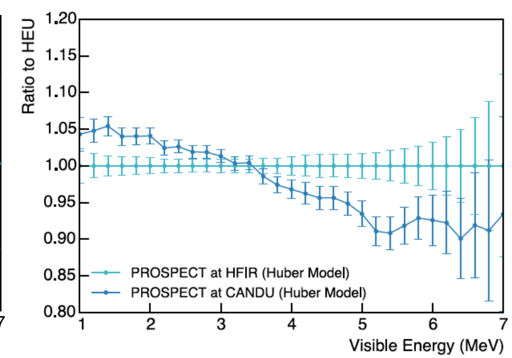
Testing $^{235}U\ \overline{\nu}_e$ spectrum models



Large improvement on ILL



Different reactor cores

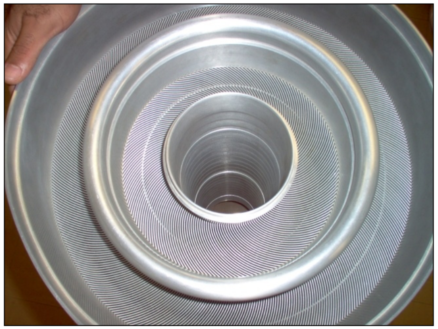


Objectives

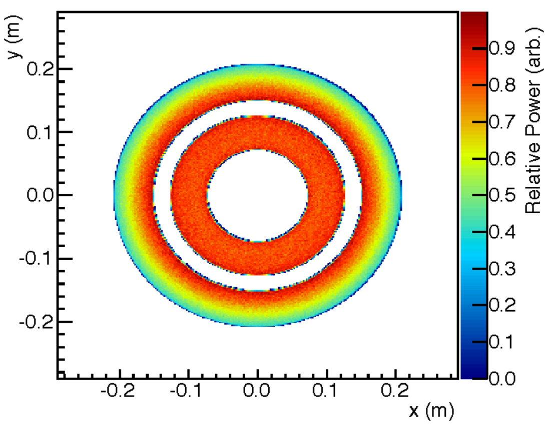
Measurement of ^{235}U spectrum
Compare different reactor models
Compare different reactor cores

Experimental site: High Flux Isotope Reactor @ORNL

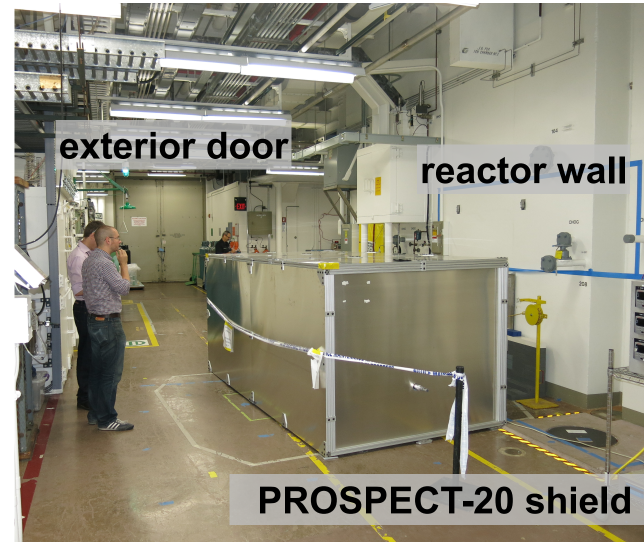
Compact Reactor Core

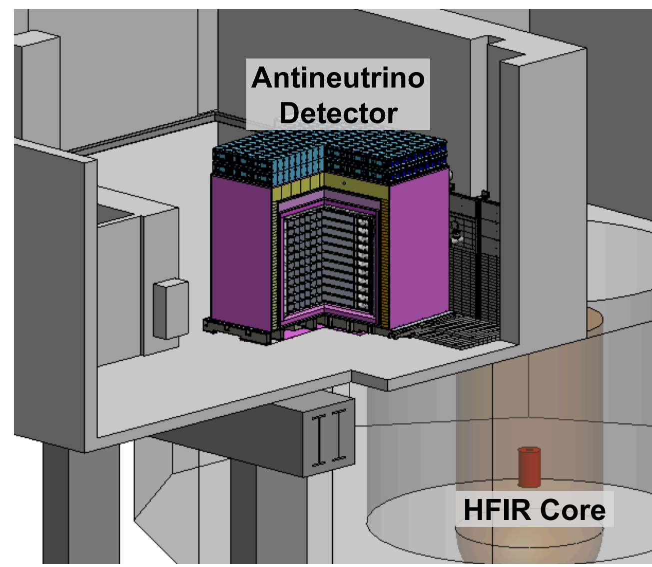


Power: 85 MW
Fuel: HEU (^{235}U)
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 41%

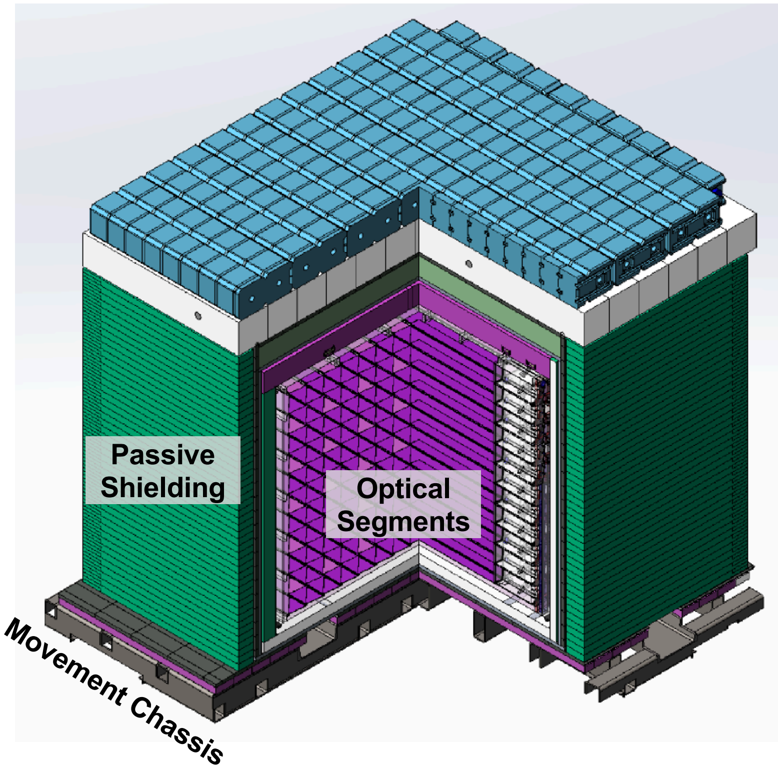


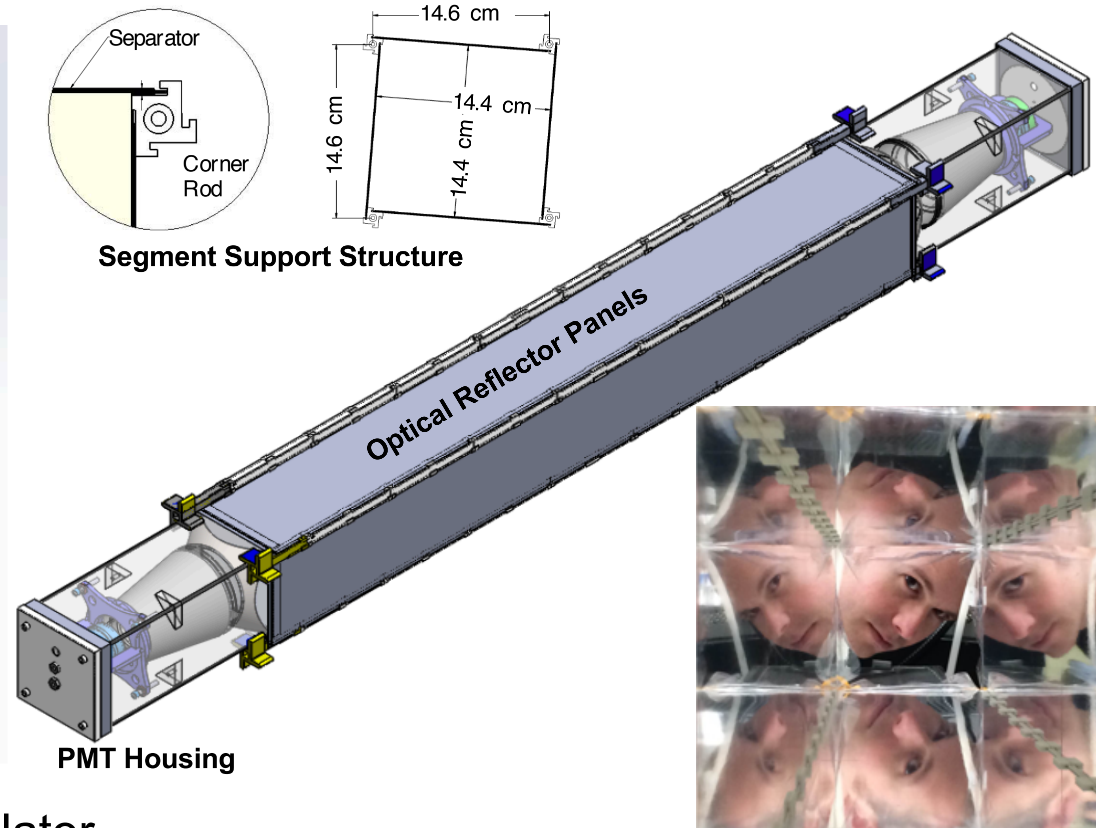
- Established on-site operation
- User facility, 24/7 access
- Exterior access at grade
- Full utility access





PROSPECT Antineutrino Detector

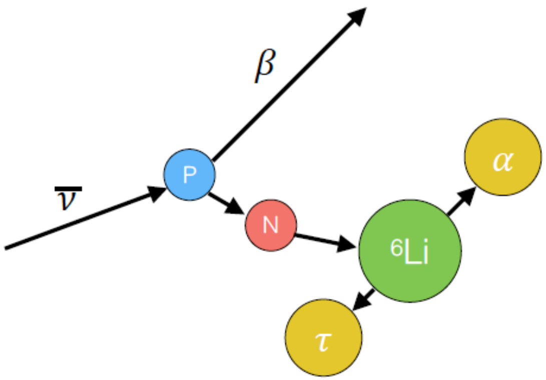




- ~4000L of ^{6}Li loaded liquid scintillator
- 11x14 segmented optical array, ~15 x 15 x 120 cm^3 segment dimensions
- Double ended PMT readout, light guides, ~4.5%/√E resolution
- Low mass optical separators, minimal dead material
- Full volume calibration access

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

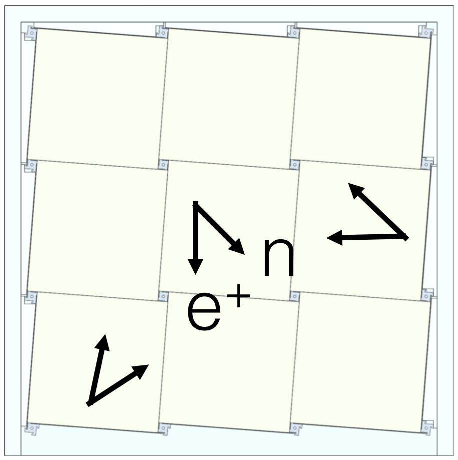
fast neutron background
recoil-like prompt, capture-like delay
capture-like prompt, capture-like delay

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

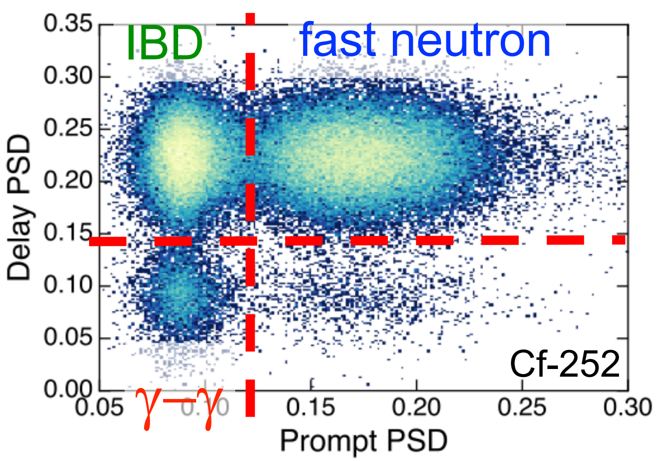
Background reduction is key challenge

Background reduction through **detector design & fiducialization**

IBD event in segmented ^{6}LiLS detector



Pulse Shape Discrimination



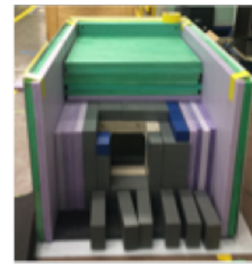
PROSPECT Detector & Shielding Development

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 length
1.7 liters
^{6}LiLS



multi-layer shielding

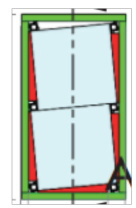
PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

1m length
23 liters
LS, ^{6}LiLS

local reactor shielding

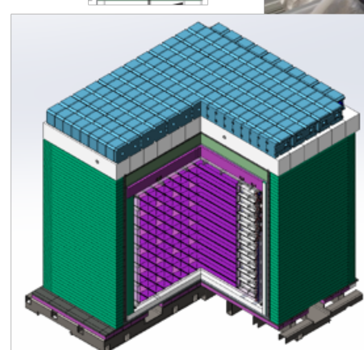
PROSPECT-50
Baseline design prototype
Spring 2016

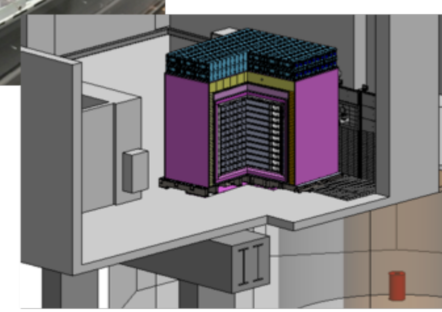
1x2 segments
1.2m length
50 liters
^{6}LiLS



PROSPECT AD
2017

11x14 segments
1.2m length
~4 tons
^{6}LiLS

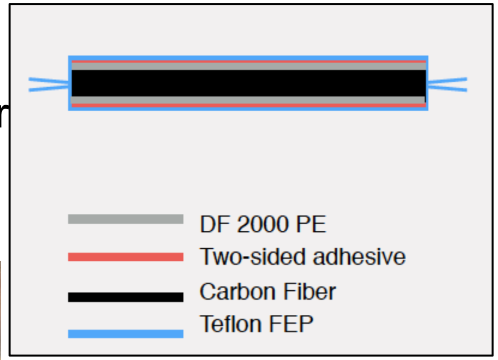




Development of PROSPECT Detector Components

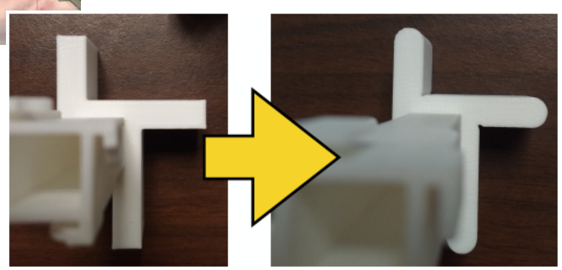
Low-Mass Optical Separators

High reflectivity, high rigidity, low mass reflector system developed

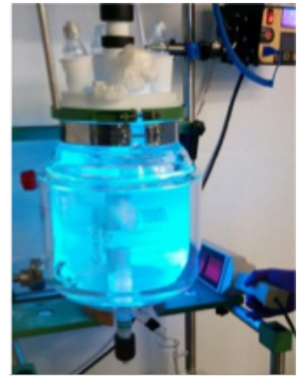


- Array formed using 3D printed "pinwheel" spacers
- Chemical compatibility of all materials validated

Component design refined for final production



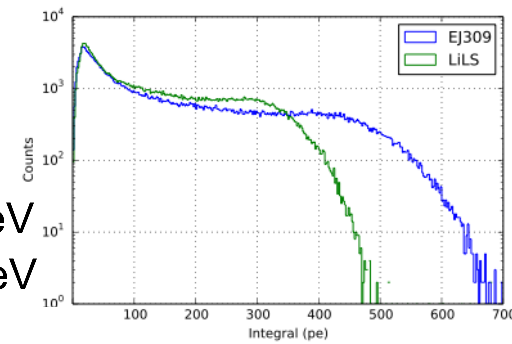
^{6}Li-Loaded Liquid Scintillator

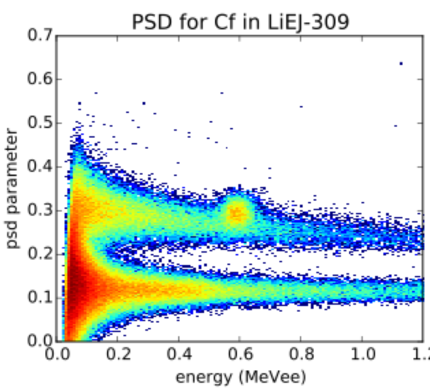


- Developed non-toxic, non-flammable formulations based on EJ-309, LAB, Ultima Gold
- EJ-309 selected as baseline

Light Yield

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





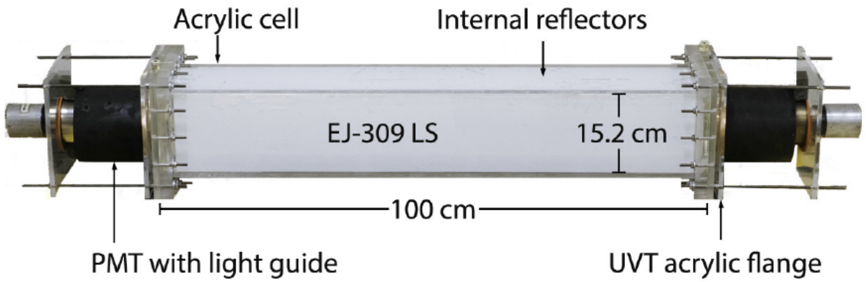
Excellent PSD performance for neutron capture & heavy recoils

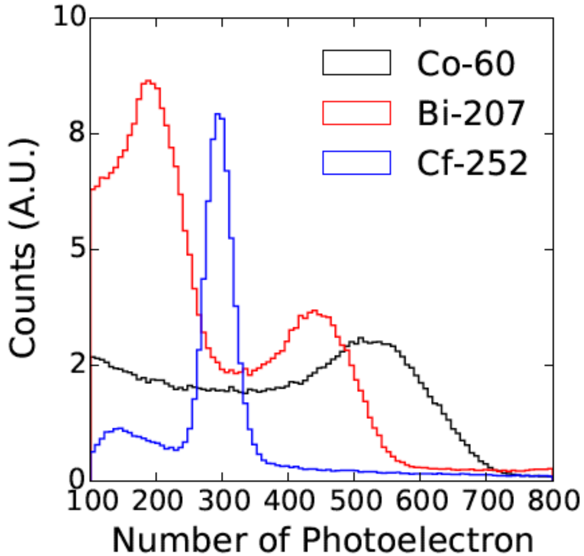
Full-scale production for PROSPECT AD underway

Full Scale Prototyping - PROSPECT20

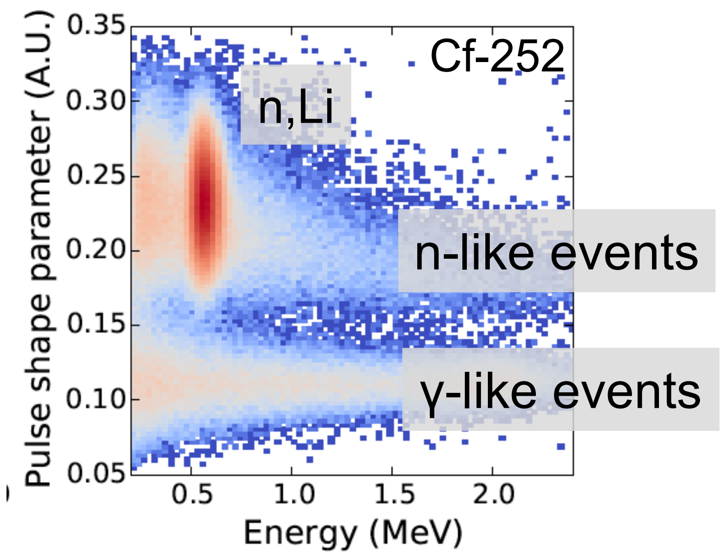
Validates optical system design

- Li-loaded liquid scintillator
- Reflector panels





Light Yield/ PE Spectra



Pulse Shape Discrimination

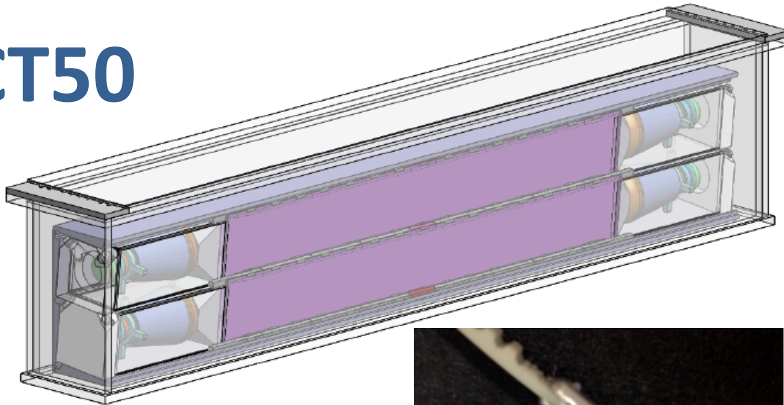
- Compton edge of ^{60}Co and ^{217}Bi γ-rays and the quenched (n, Li) capture peak from ^{252}Cf neutrons
- light collection: **522±16 PE/MeV**

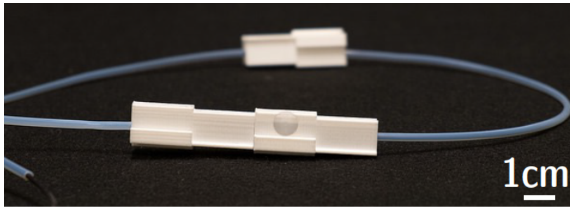
Unloaded LS studies described in 2015 JINST 10 P11004, arXiv:1508.06575, PROSPECT collaboration

System Prototyping – PROSPECT50

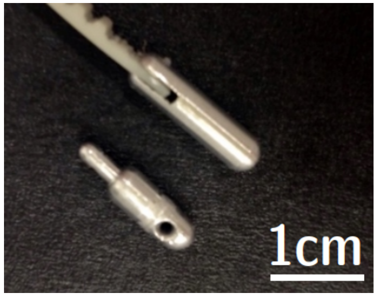
Validates AD component design

- Low-mass Optical Separators
- Support Structure
- PMT modules
- Filling System
- Calibration: LED & γ/n Sources

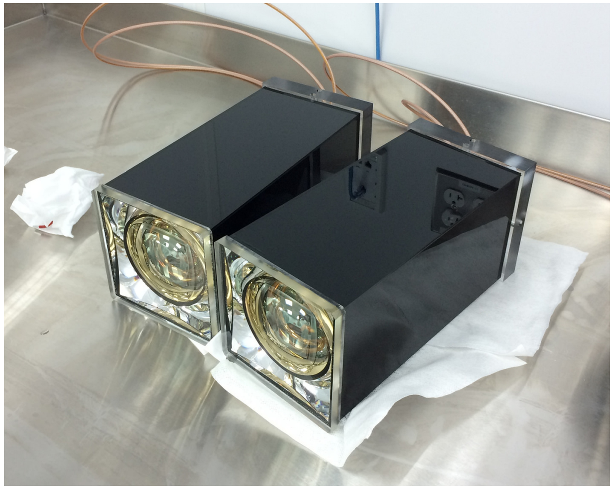




Mid-Segment LED Calibration

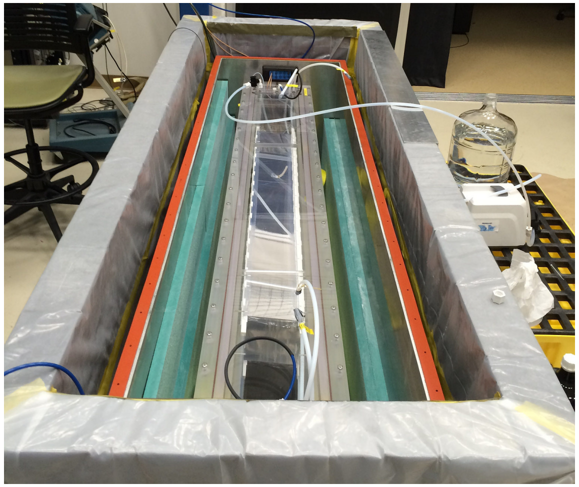


Source Capsule



PMT Modules

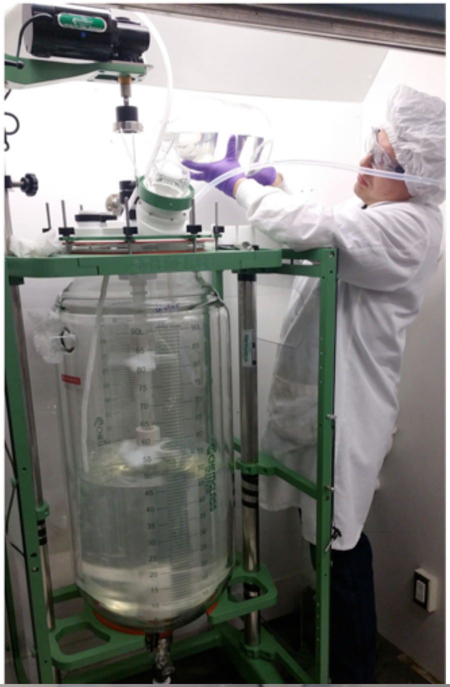
Segment Assembly



P-50 Installed in Shield

PROSPECT50 performance as expected based on earlier prototypes

AD Construction is underway

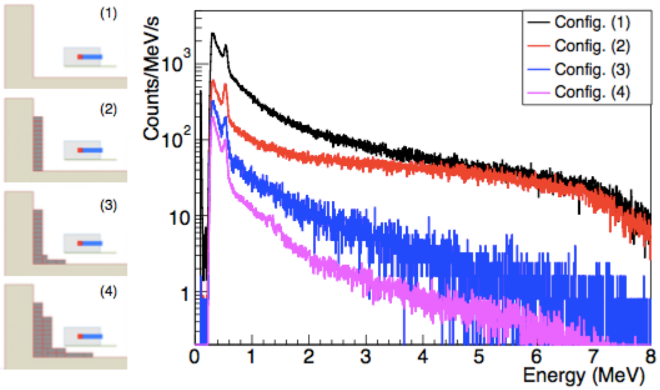


Reactor Background Measurement & Shield Design

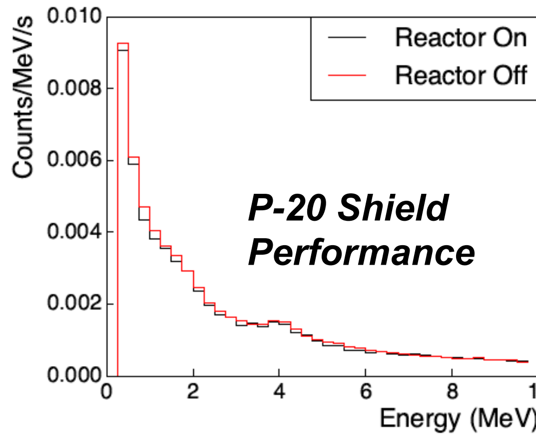
Shield design based on surveys & multiple onsite prototype deployments

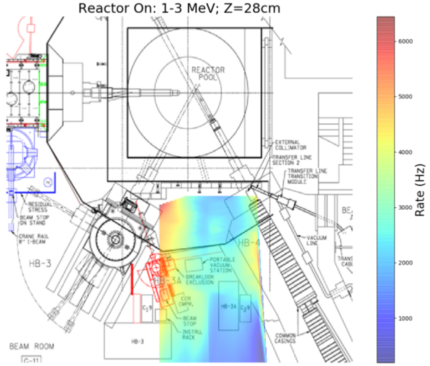
Extensive measurement campaigns (*ongoing*):

- Characterize background field at HFIR
- Emphasize importance of localized shielding of penetrations, pipes, etc



Localized shielding studies



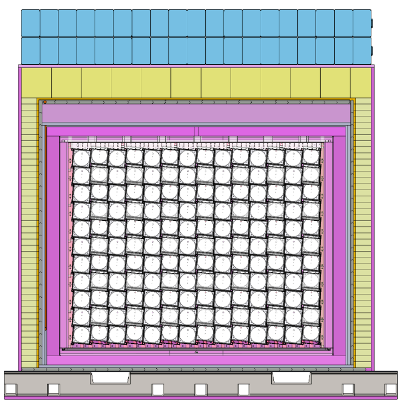


γ-ray intensity variation at HFIR

Nucl. Instrum. Meth. A806 (2016) 401–419, arXiv:1506.03547, PROSPECT Collaboration

PROSPECT AD Shielding

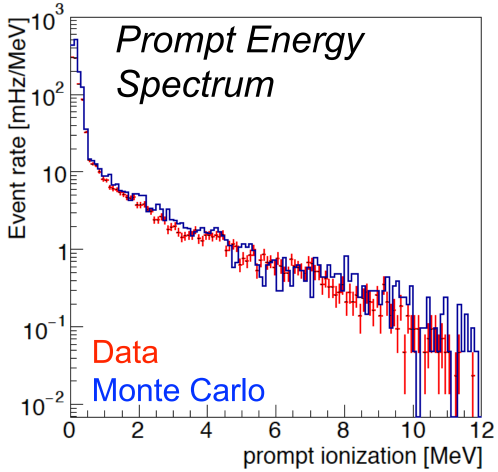
- local shielding next to reactor wall
- multi-layer passive shield:
  - water bricks, HDPE, borated HDPE, lead

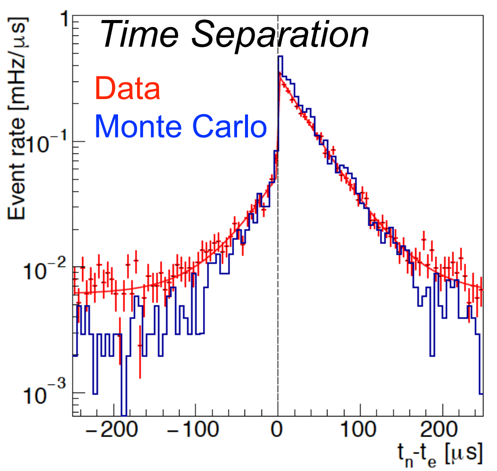


AD-1 Multi-Layer Shield

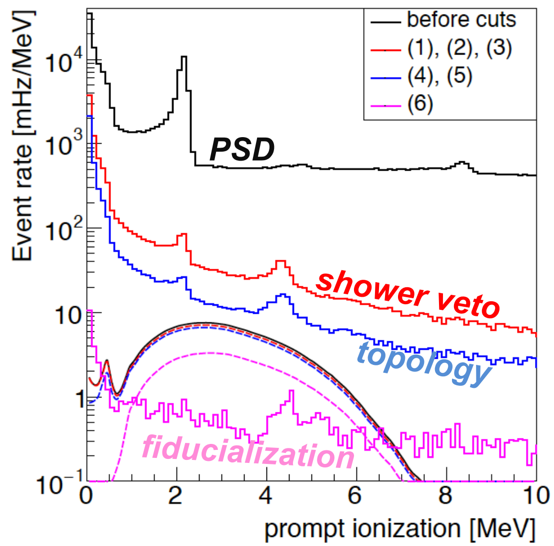
Signal to Background Prediction

Prototype systems provide benchmarking of AD Monte Carlo



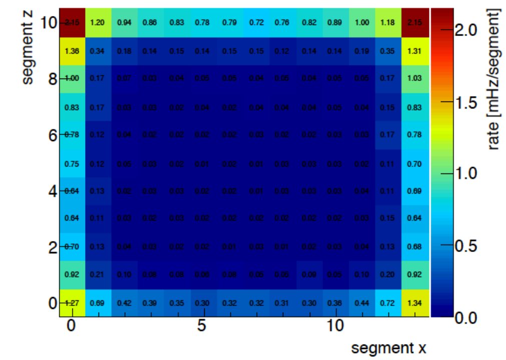


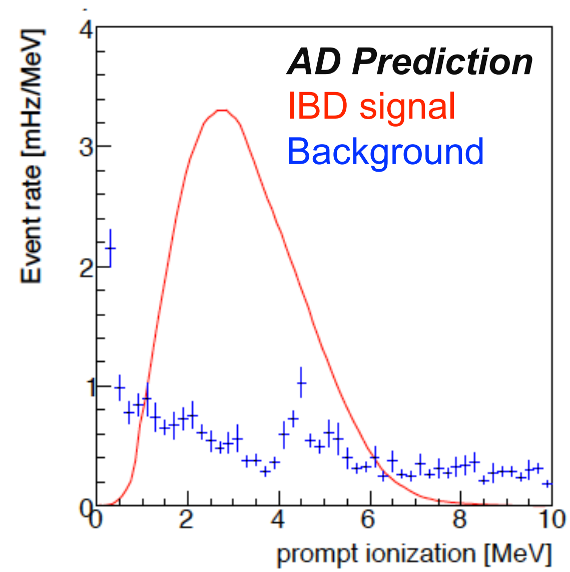
PROSPECT20 Correlated Background Measurements



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.

PROSPECT Collaboration

Supported by:

prospect.yale.edu

Conclusion

- New data are required to address the rate and spectrum reactor anomalies
- PROSPECT will
  - Probe favored region for eV-scale sterile neutrinos at >3σ with 3 years of data
  - Measure the ^{235}U $\bar{\nu}_e$ spectrum, addressing the observed spectral deviation, and providing new constraints on reactor antineutrino models complementary to current and future LEU measurements
- The PROSPECT R&D Program has:
  - developed LiLS detector technology that can mitigate reactor- and cosmogenic related backgrounds
  - Deployed multiple detectors at HFIR to validate models and operating procedures and prepare for full-size system deployment
  - Completed validation of system components for full scale production
- Antineutrino Detector construction is underway
- Installation expected in 2017