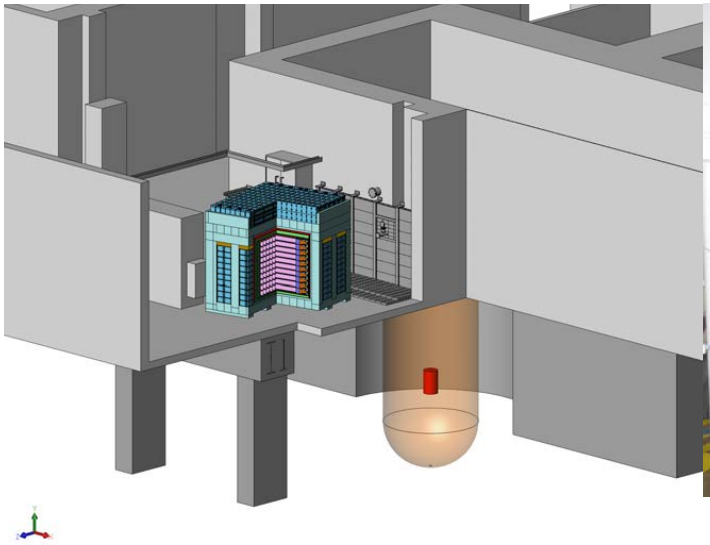
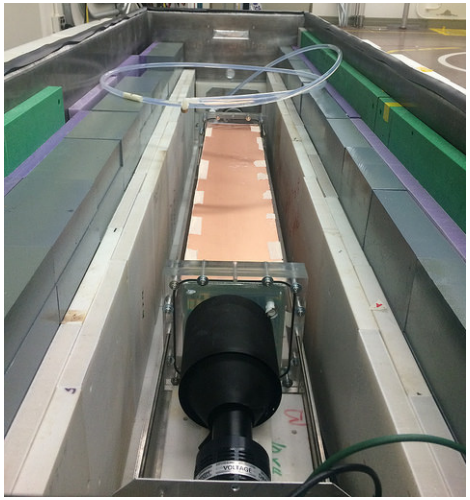
A Precision Oscillation and Spectrum Experiment





Karsten M. Heeger
Yale University

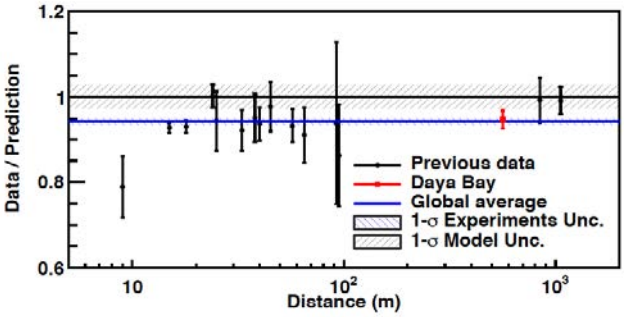
on behalf of the PROSPECT collaboration
prospect.yale.edu

AAP2015, December 7, 2015

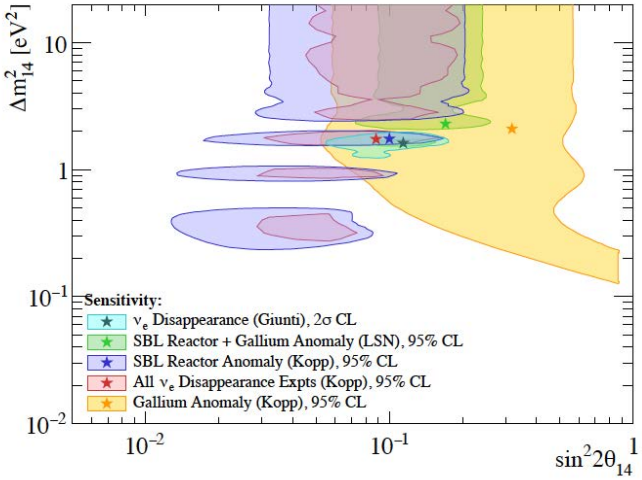
A Short-Baseline Reactor Neutrino Experiment

Search for sterile neutrinos through neutrino oscillations

Test reactor anomaly

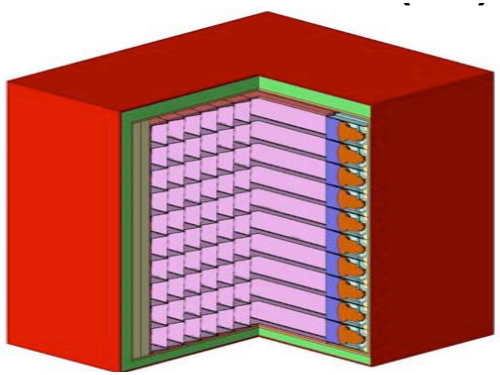


Test allowed oscillation parameter space



Measurement of the Relative Reactor Flux and Spectrum at Different Baselines

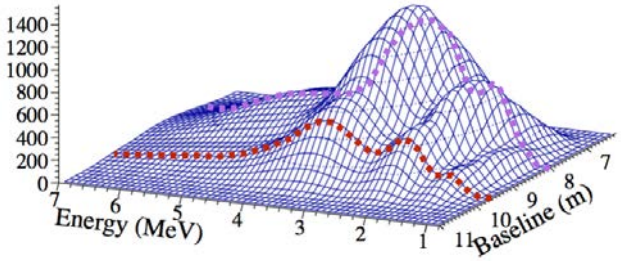
independent of reactor models/predictions



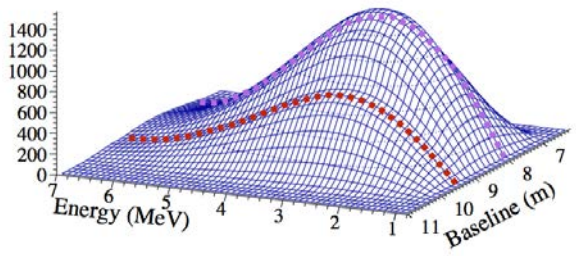
Segmented detector

Relative measurement within detector

oscillated spectrum



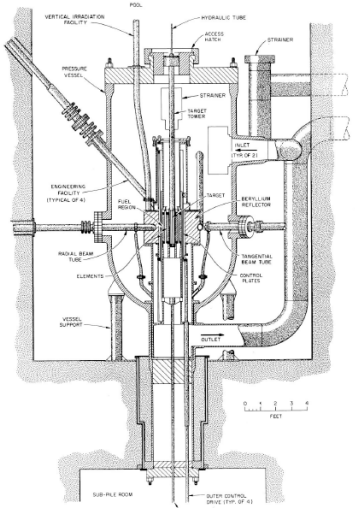
unoscillated spectrum



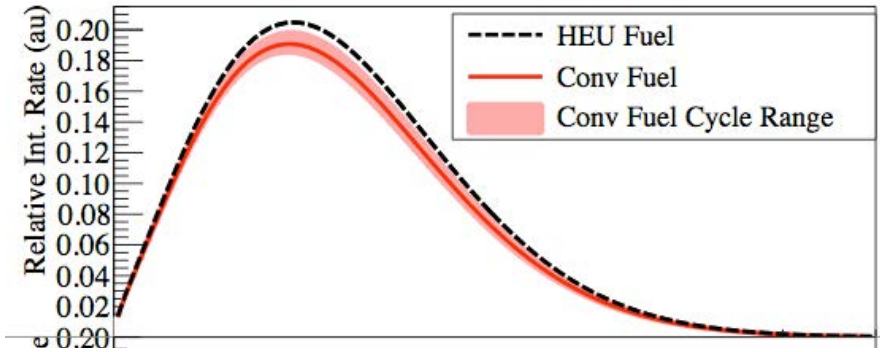
each segmented measures L/E

High Flux Isotope Reactor, Oak Ridge National Lab

US Research Reactor



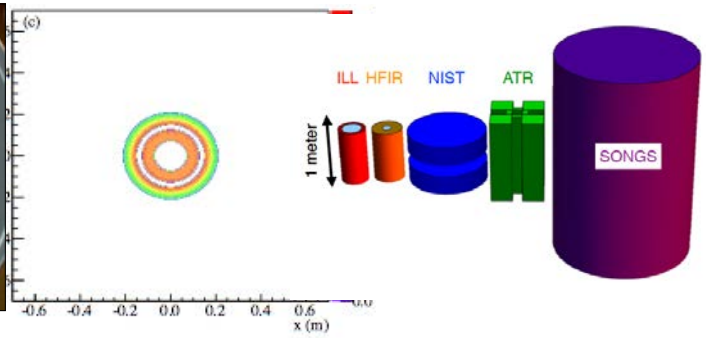
Research Reactor Spectrum



HEU core provides static spectrum of mainly ^{235}U.

power: 85 MW (research)
fuel: highly enriched uranium (^{235}U)
core shape: cylindrical
size: h=0.5m r=0.2m (compact)
duty-cycle: 41%

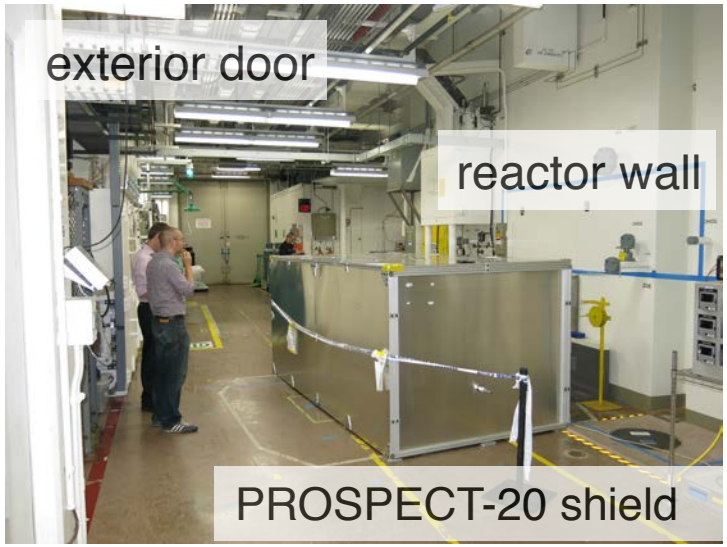
Compact reactor core

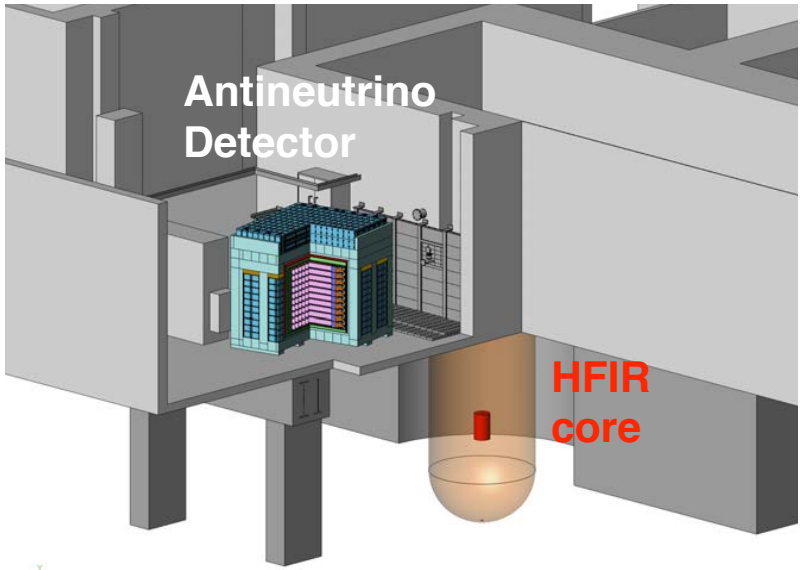


Nucl. Instrum. Meth. A806 (2016) 401–419,
arXiv:1506.03547,
PROSPECT collaboration

Compact core (< 1m) avoids oscillation washout

PROSPECT Experimental Location





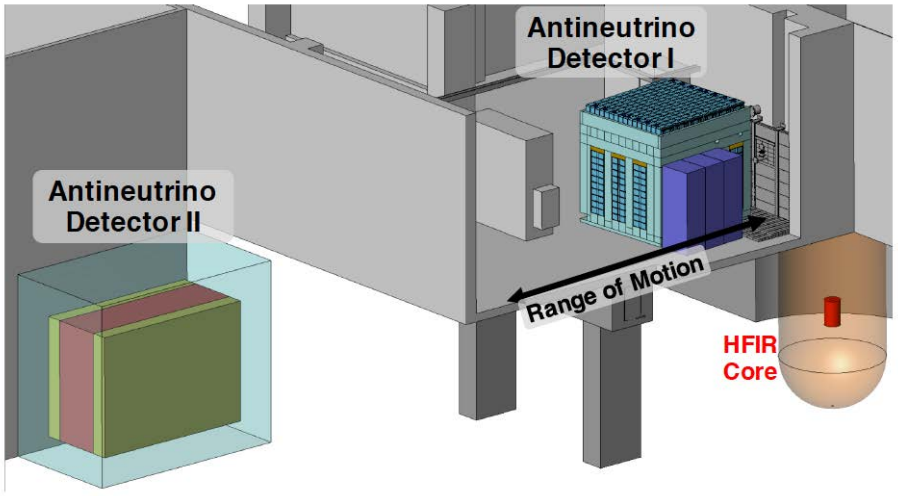
- established on-site operation
- easy access 24/7, user facility
- door to outside
- internet access, utilities

PROSPECT Experiment

Physics Objectives

1. Search for short-baseline oscillation at distances <10m
2. Precision measurement of ^{235}U reactor $\bar{\nu}_e$ spectrum

One Experiment, 2 Detectors



Phase I
one movable detector AD-I,
~7-12 m baseline

Phase II
two detectors,
movable AD-I, ~7-12m baseline
stationary AD-II, ~15-19m baseline

- movable detector enables systematic control, background checks, and increased physics reach

- phased approach mitigates risks

whitepaper, arXiv:1309.7647
PROSPECT collaboration

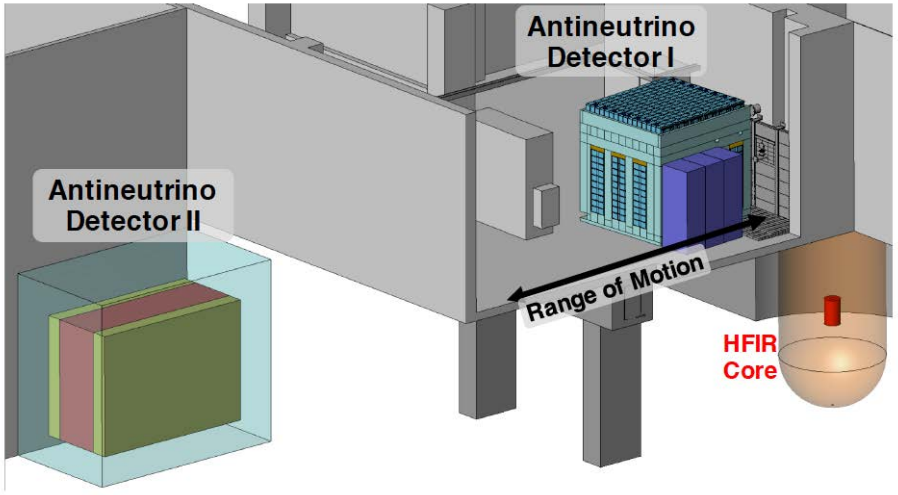
physics program, on arXiv this week
PROSPECT collaboration

PROSPECT Experiment

Physics Objectives

1. Search for short-baseline oscillation at distances <10m
2. Precision measurement of ^{235}U reactor $\bar{\nu}_e$ spectrum

One Experiment, 2 Detectors



Parameter	Value
Reactor	
Power	85 MW
Shape	Cylinder
Size	0.2 m r × 0.5 m h
Fuel	HEU
Duty cycle	41% reactor-on
Antineutrino Detector 1 (AD-I)	
Cross-section	1.2×1.45 m^2
Proton density	5.5×10^{28} p/m^3
Total Target Mass	2940 kg
Fiducialized Target Mass	1480 kg
Baseline range	4.4 m
Efficiency in Fiducial Volume	42%
Position resolution	15 cm
Energy resolution	$4.5\%/\sqrt{E}$
S:B Ratio	3.1, 2.6, 1.8
Closest distance	6.9 m, 8.1 m, 9.4 m
Antineutrino Detector 2 (AD-II)	
Total Target Mass	~10 ton
Fiducialized Target Mass	~70%
Baseline range	~4 m
Efficiency in Fiducial Volume	42%
Position resolution	15 cm
Energy resolution	$4.5\%/\sqrt{E}$
S:B ratio	3.0
Closest distance	15 m
Operational Exposure	
Phase I	1, 3 years
Phase II	3 years

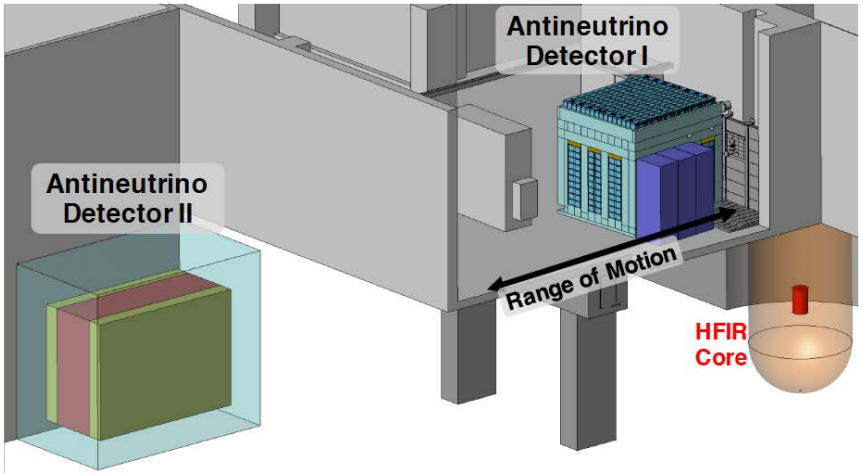
whitepaper, arXiv:1309.7647
PROSPECT collaboration

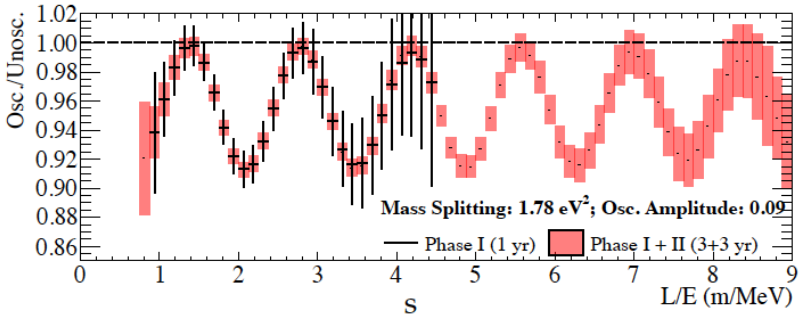
physics program, on arXiv this week
PROSPECT collaboration

PROSPECT Physics

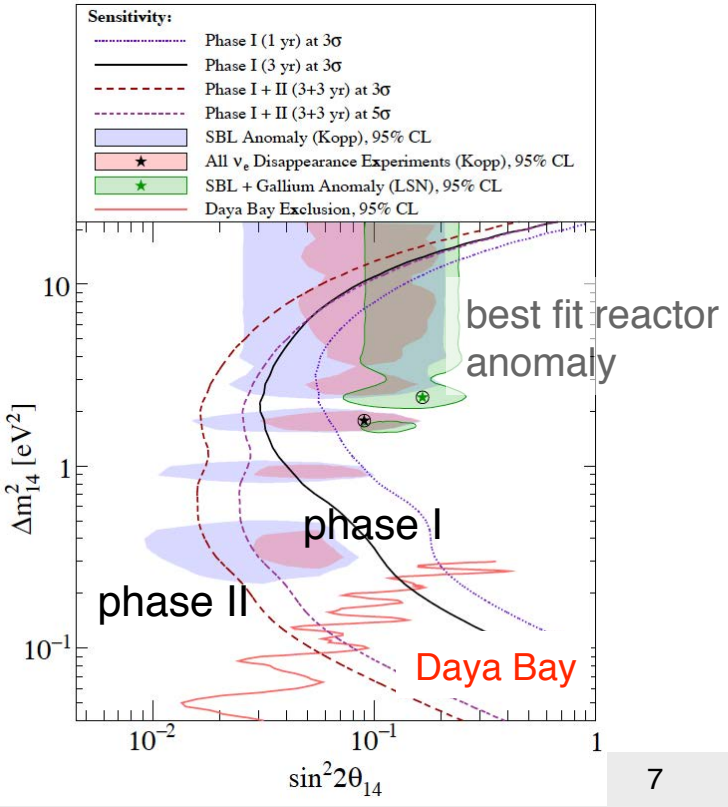
A Precision Oscillation Experiment

An experimental approach to test for oscillation of eV-scale neutrinos





Phase I = AD-I, 3 years
Phase II = AD-I + AD-II, 3+3 years



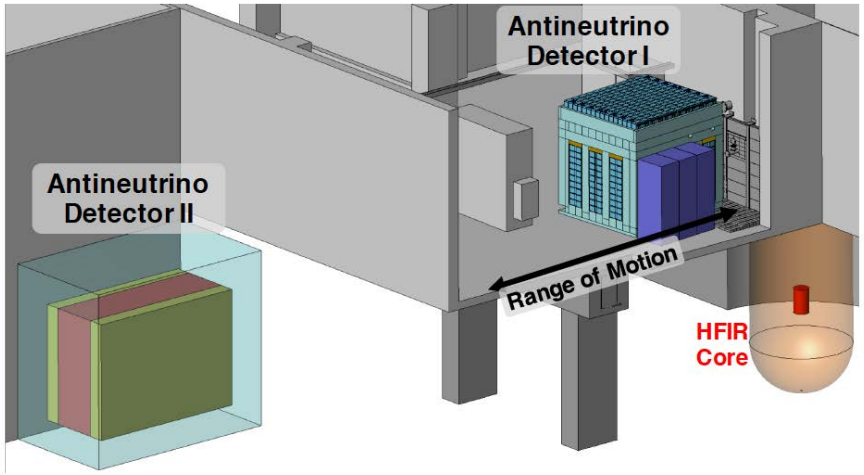
Objectives

4σ test of best fit after 1 year
>3σ test of favored region after 3 years
5σ test of allowed region after 3+3 years

PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns



Phase I = AD-I only

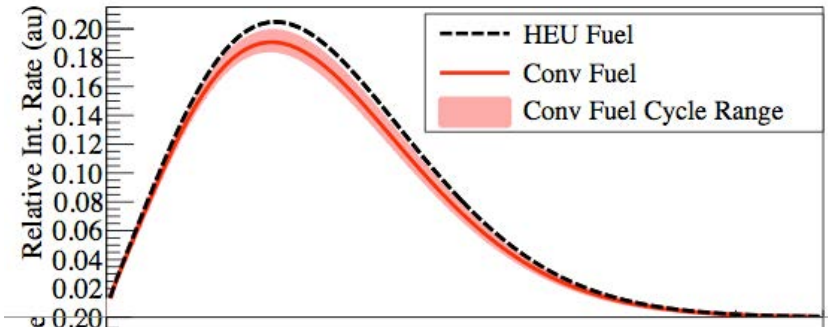
Objectives

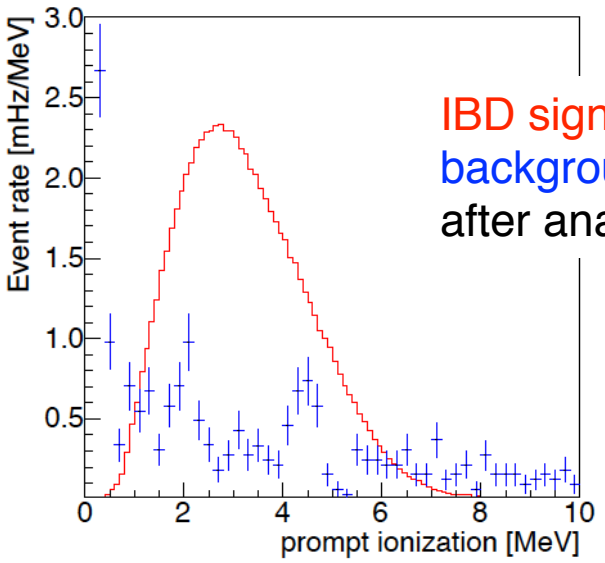
Measurement of ^{235}U spectrum

Compare different reactor models

Compare different reactor cores

Measurement of HEU (^{235}U) spectrum





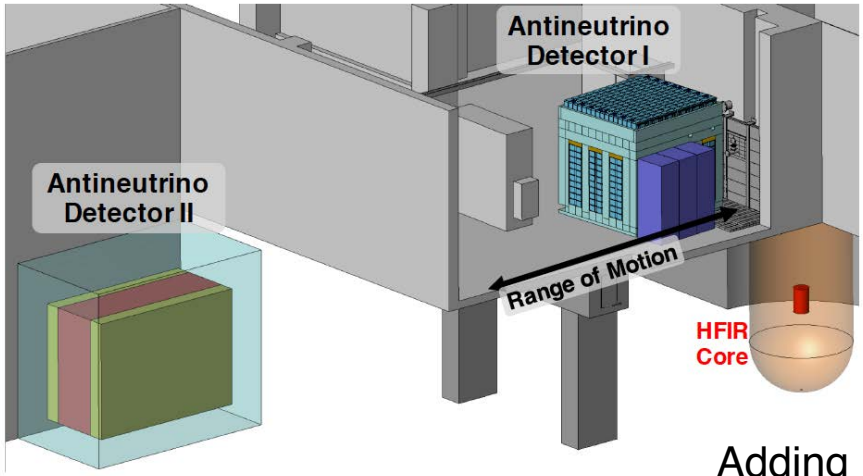
IBD signal backgrounds after analysis cuts

between 2-6 MeV:
average stat. precision < 1.5%, systematics < 2%

PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns



Phase I = AD-I only

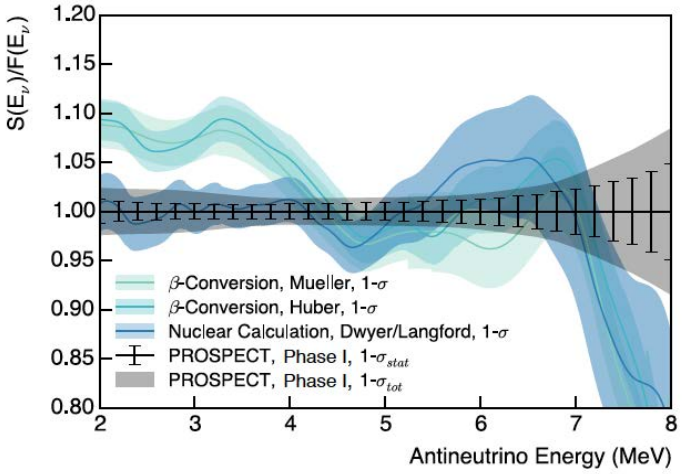
Objectives

Measurement of ^{235}U spectrum

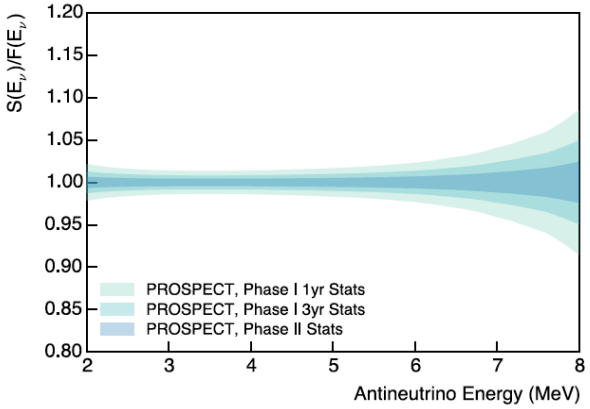
Compare different reactor models

Compare different reactor cores

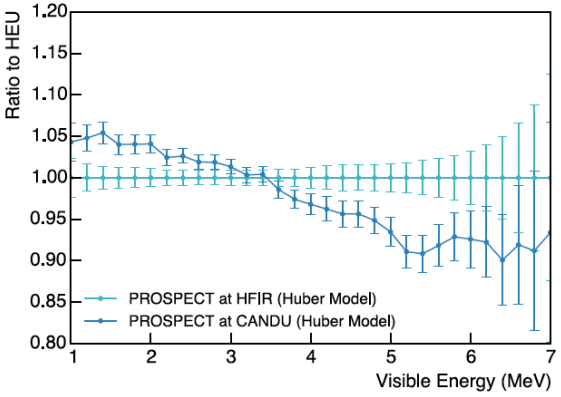
Testing models of the ^{235}U $\overline{\nu}_e$ energy spectrum



Adding Phase II Detector

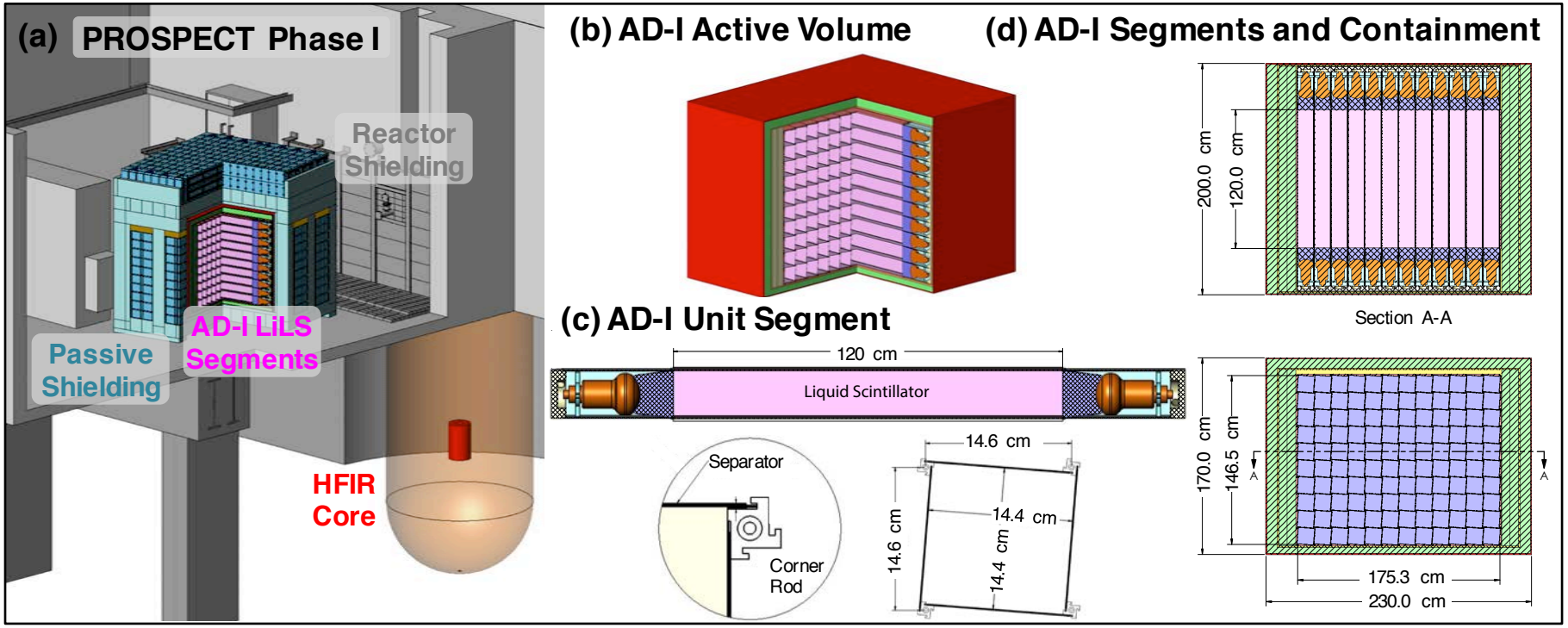


Different reactor cores



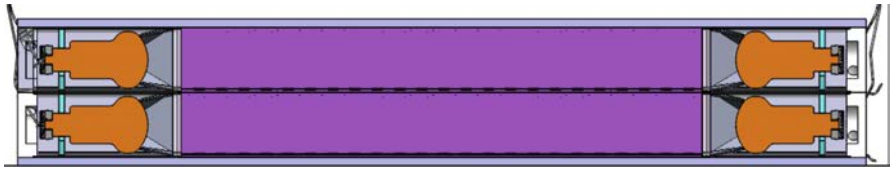
PROSPECT Phase I Detector System

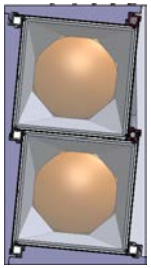
Antineutrino Detector

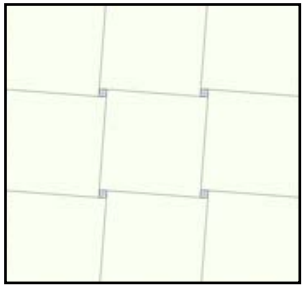


Antineutrino Detector Segments

PMT
Light Guide
Optical Separator
^{6}LiLS

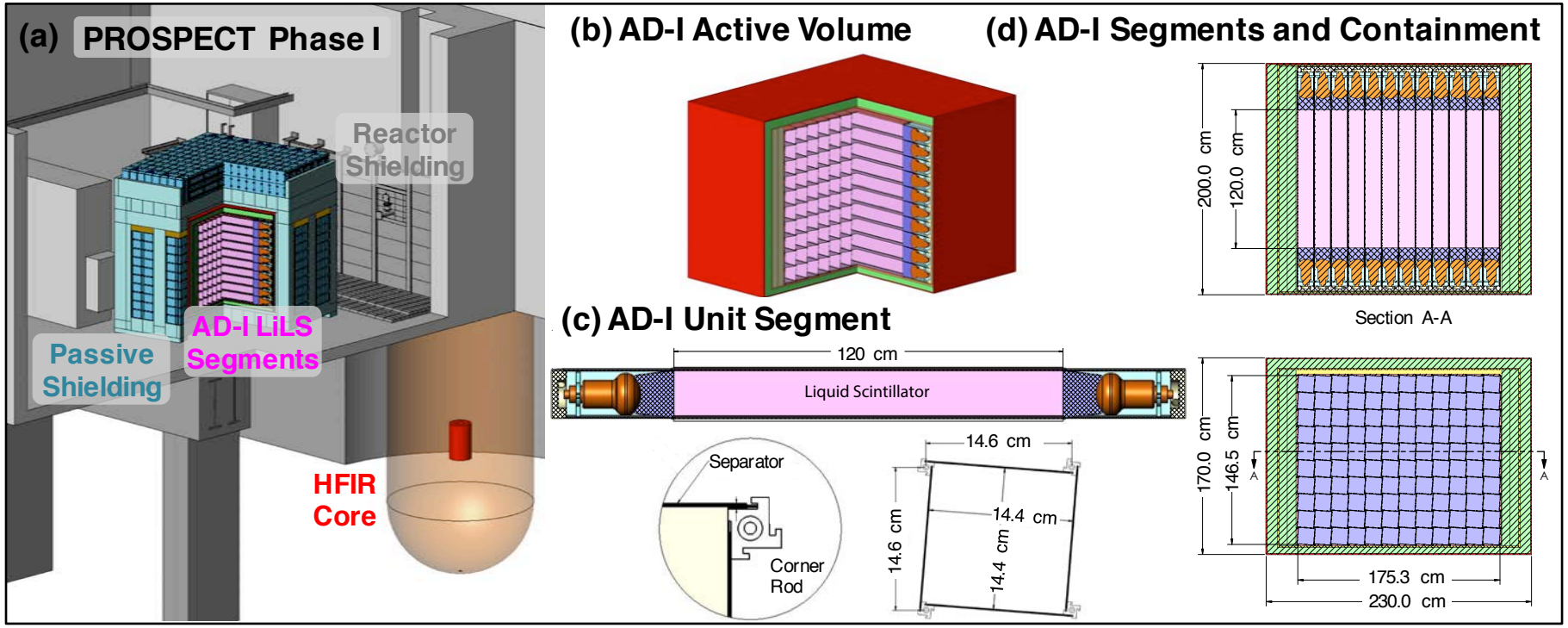






PROSPECT Phase I Detector System

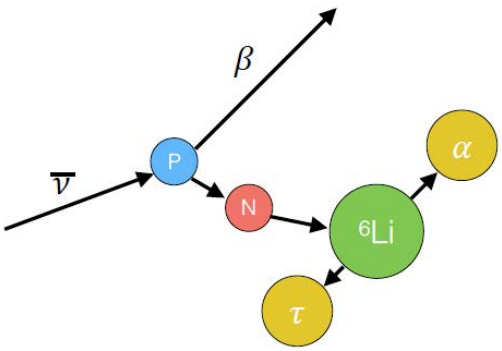
Antineutrino Detector



- 3000L of ^{6}Li liquid scintillator
- 120 scintillator loaded cells, ~15x15x120cm
- double ended PMT readout, light guides, <4-5%/√E resolutions
- thin optical separators, minimal dead material
- containment vessel, filled in place

PROSPECT Event Detection

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

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

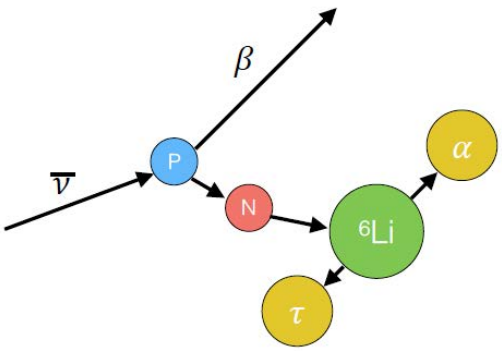
backgrounds — fast neutron
n-like prompt, n-like delay

accidental gamma
γ-like prompt, γ-like delay

Background reduction is key challenge

PROSPECT Event Detection

Event Identification



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γ-like prompt, n-like delay

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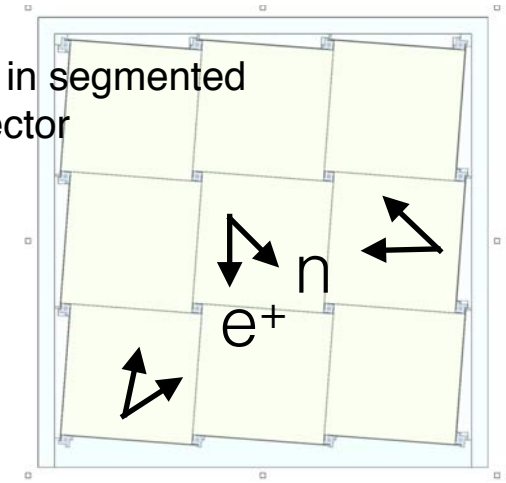
accidental gamma
γ-like prompt, γ-like delay

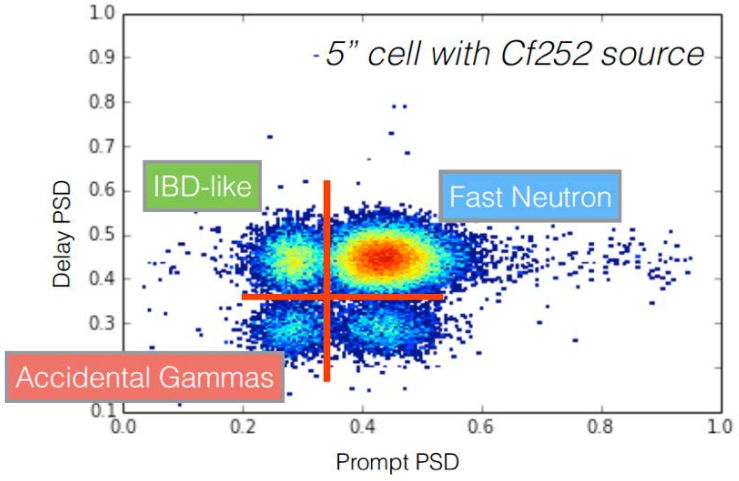
Background reduction is key challenge

Background Reduction through **detector design & fiducialization**

IBD event in segmented ^{6}LiLS detector



Pulse Shape Discrimination

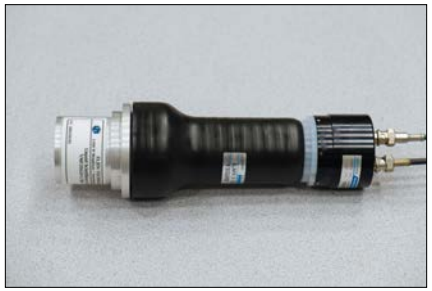


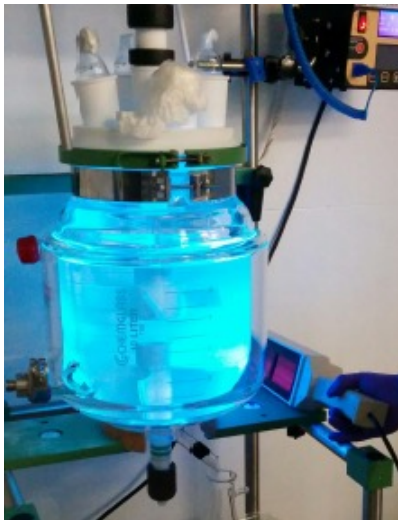
Lithium-loaded Liquid Scintillator

Development

Novel scintillator cocktail:

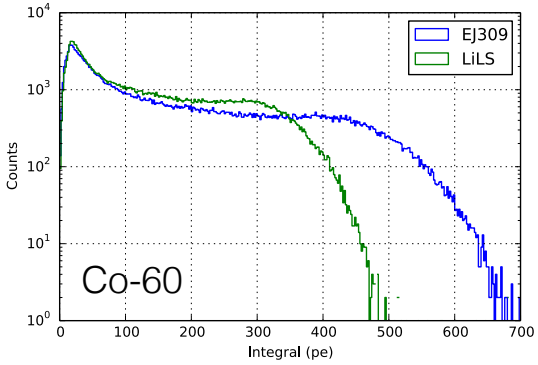
- PSD LiLS that is non-toxic, non-flammable
- extensive studies with LAB, Ultima Gold
- EJ-309 gave best light yield, PSD

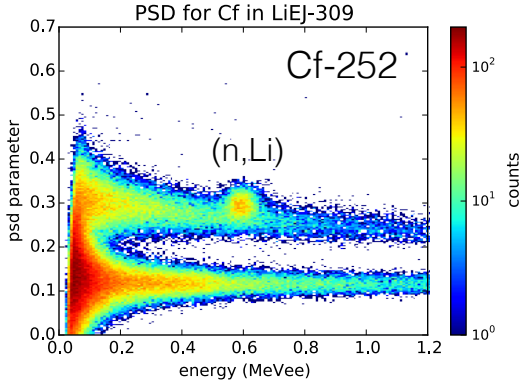


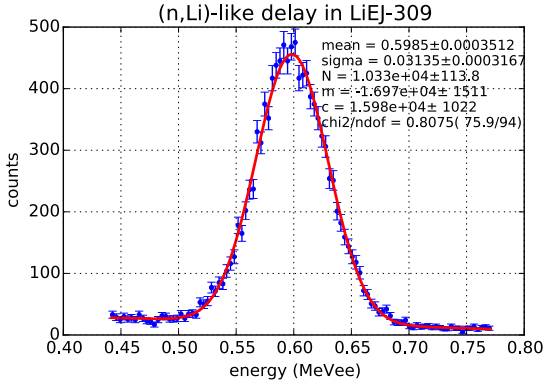


Scintillator specs (PROSPECT-0.1):

- Light Yield$_{EJ\text{-}309}$ = 11500 ph/MeV
- Light Yield$_{LiLS,\ measured}$ = 8200 ph/MeV
- prominent neutron capture peak in LiLS
- PSD FOM at (n, Li) is 1.79
- energy resolution (σ/E) of 5.2% at 0.6MeV$_{ee}$



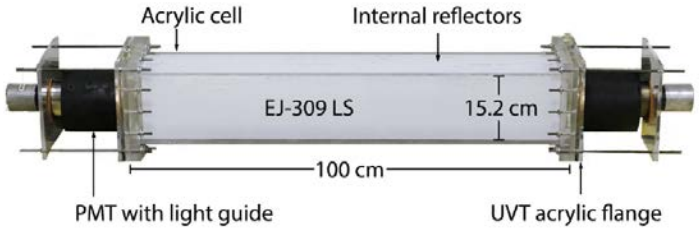




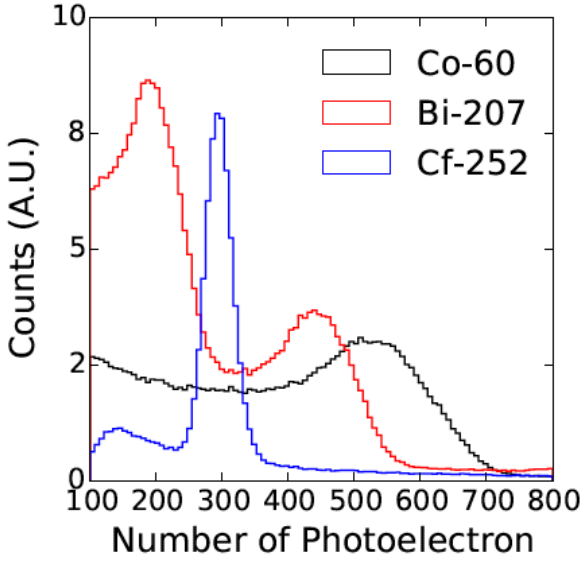
developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities
PSD critical for background reduction

PROSPECT Scintillator Target

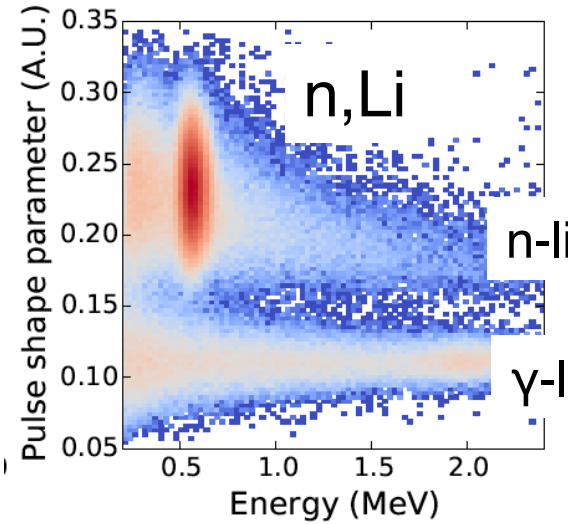
Prototype Detectors
PROSPECT-20 w/ LiLS and Unloaded LS



Light Yield/ PE Spectra



Pulse Shape Discrimination



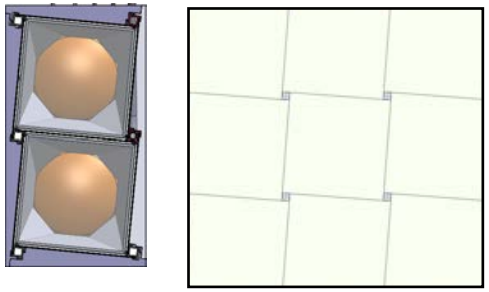
PSD performance for Cf-252.

- 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

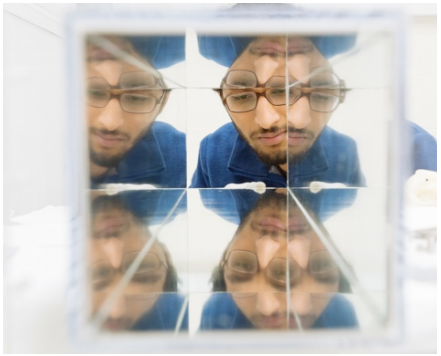
unloaded LS studies described in
2015 JINST 10 P11004, arXiv:1508.06575,
PROSPECT collaboration

Antineutrino Detector Segmentation

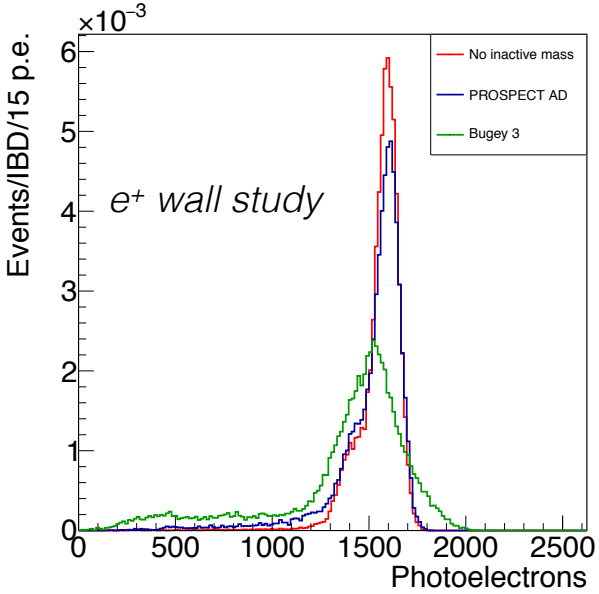
Low-mass, optical separators



minimum dead material

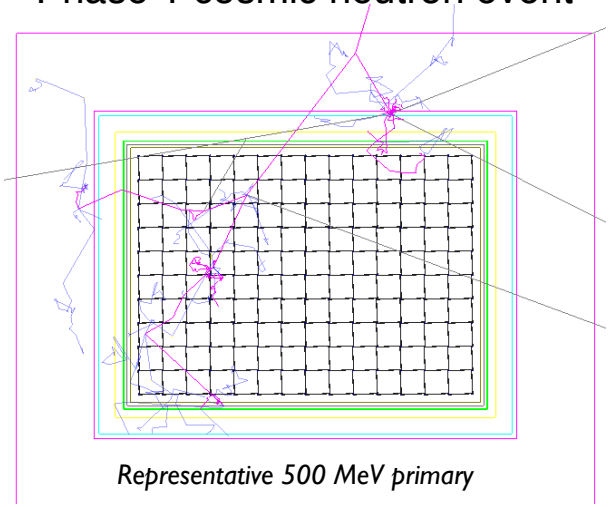


Low-mass reflector prototypes

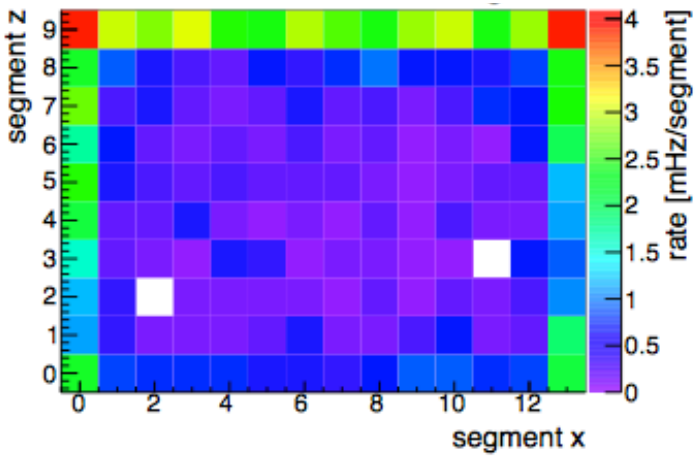


Fiducialization

Phase 1 cosmic neutron event

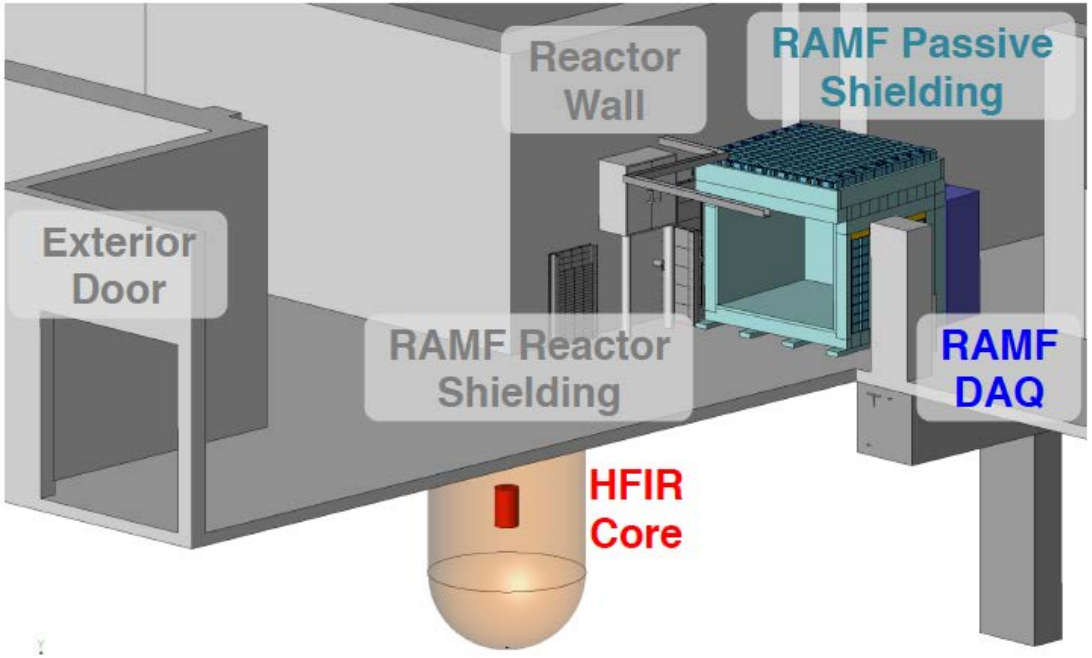


Phase I AD-1, IBD-like neutron segment

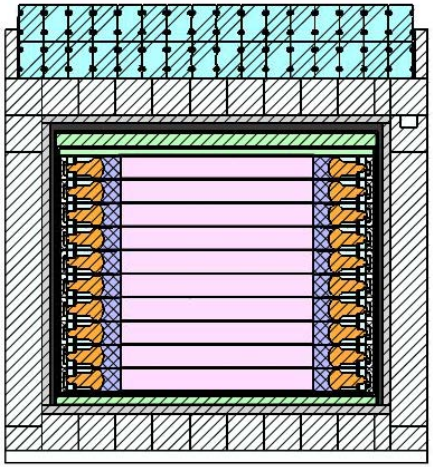


PROSPECT Shielding

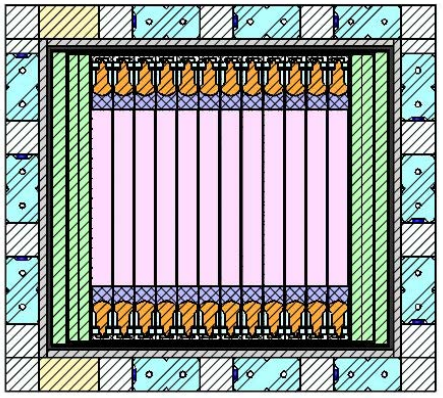
Reactor Antineutrino Measurement Facility (RAMF) at HFIR



Layered Shielding side view



top view

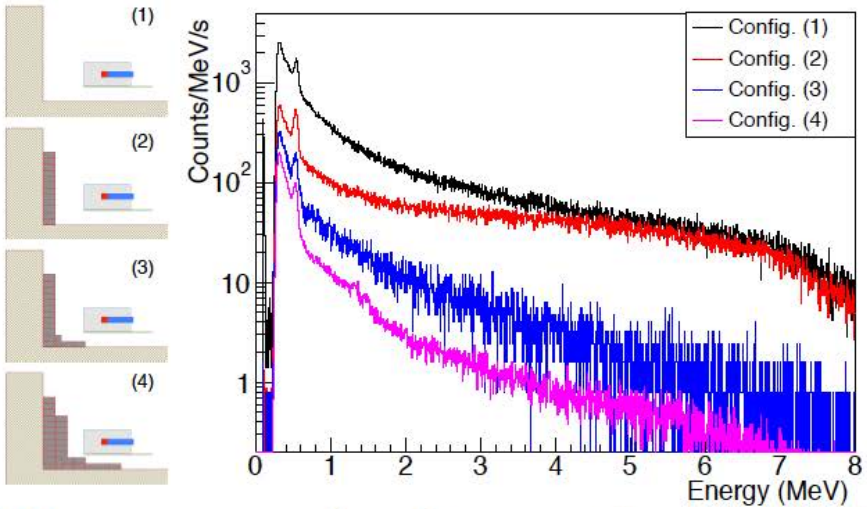


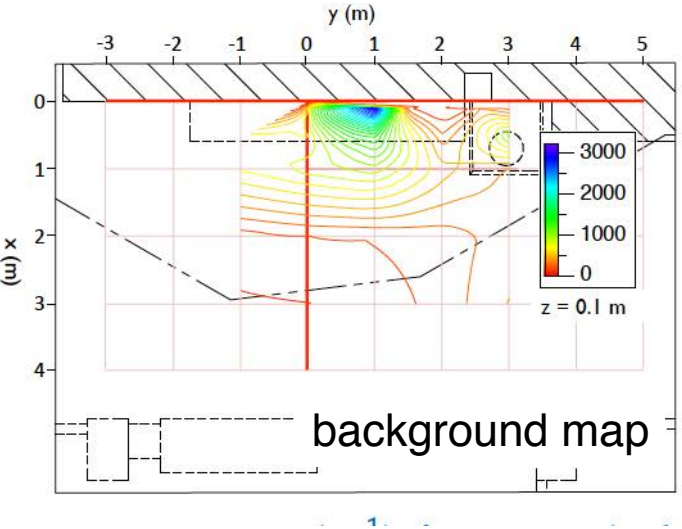
- local shielding next to reactor wall
- multi-layer passive shield around detector (water bricks, HDPE, borated HDPE, lead)
- general purpose digitizing electronics and DAQ
- general utilities
- easy access

PROSPECT Backgrounds at HFIR

Background Measurements at HFIR

varying reactor shields

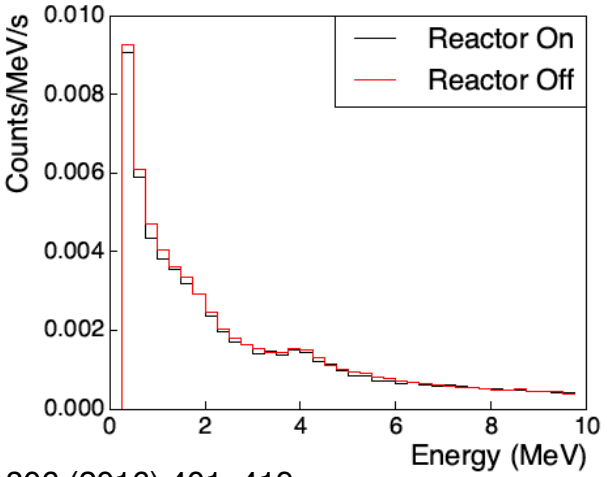




IBD-like events for reactor-on and off

reactor generated backgrounds are minimal

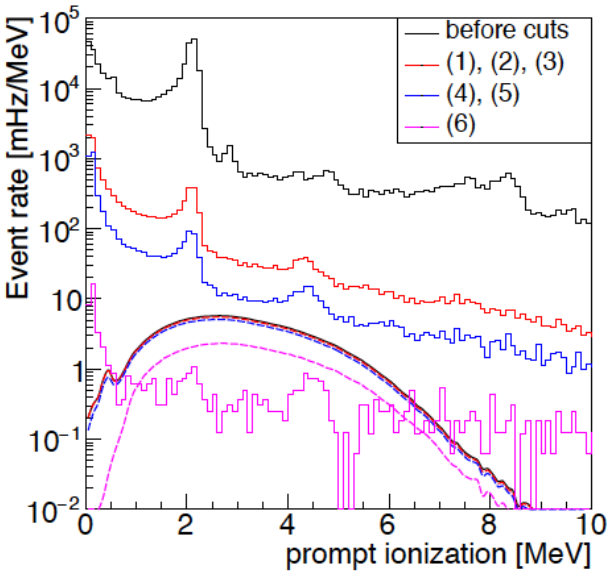
IBD-like backgrounds are cosmogenic

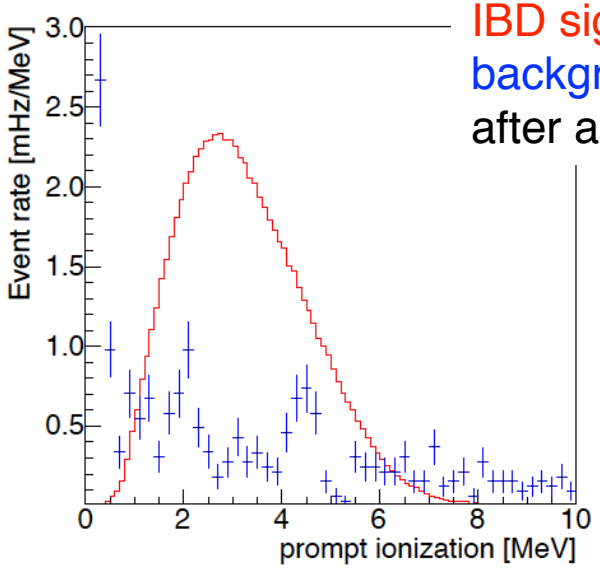


Nucl. Instrum. Meth. A806 (2016) 401–419, arXiv:1506.03547, PROSPECT collaboration

PROSPECT Signal & Background

Simulated Signal and Background Spectra





IBD signal
backgrounds
after analysis cuts

Signal (dashed) and background (solid) prompt spectra are shown through selection cuts

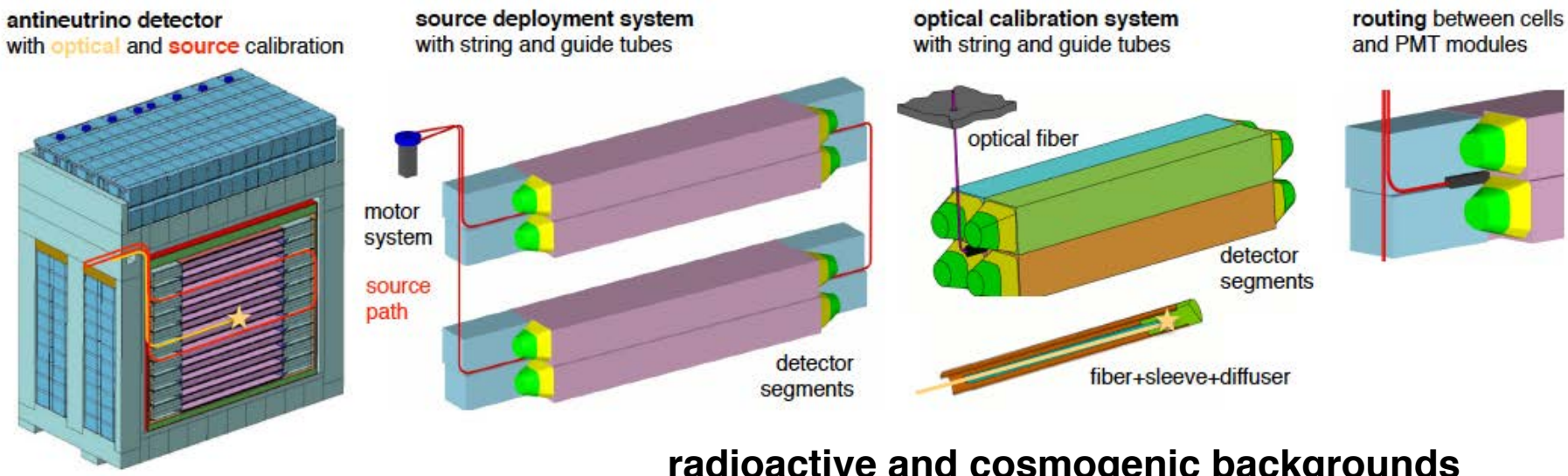
S/B better than 1:1 is predicted.

Rate and shape of the residual IBD-like background can be measured with high precision during reactor off periods.

Cuts	IBD signal	Cosmic BG
PSD	1630	2.1e6
Time (1, 2, 3)	1570	3.4e4
Spatial (4, 5)	1440	9900
Fiducial (6)	660	250

simulated event rates, $0.8 \leq E \leq 7.2$ MeV
after applying background rejection cuts

PROSPECT Calibration



pulsed laser sources
- LiLS light transmission
- PMT gain and timing

encapsulated γ sources
- energy scale
- scintillator non-linearity

neutron sources
- PSD calibration
- neutron detection efficiency

radioactive and cosmogenic backgrounds will be used to monitor and calibrate detector response between source deployments

Example: PROSPECT-20
- through going muons
- ^{40}K
- n capture on ^{6}Li

R&D on scintillator spiking with ^{227}Ac
- segment uniformity, relative LiLS mass measurements

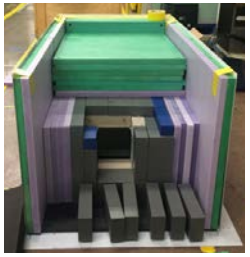
PROSPECT Detector and Shielding at HFIR Development

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

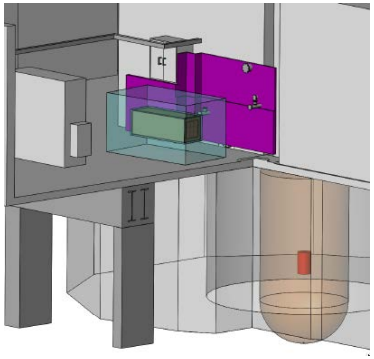
12.5 length
1.7 liters
^{6}LiLS



multi-layer
shielding

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

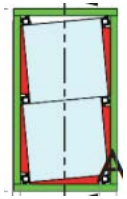
1m length
23 liters
LS, ^{6}LiLS



local reactor
shielding

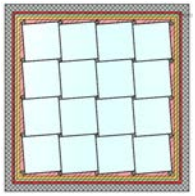
PROSPECT-50
Baseline design prototype
Winter 2015

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



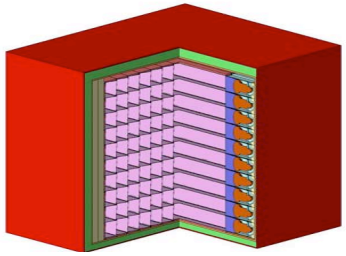
PROSPECT-400*
Fiducialization and background studies
Mid 2016

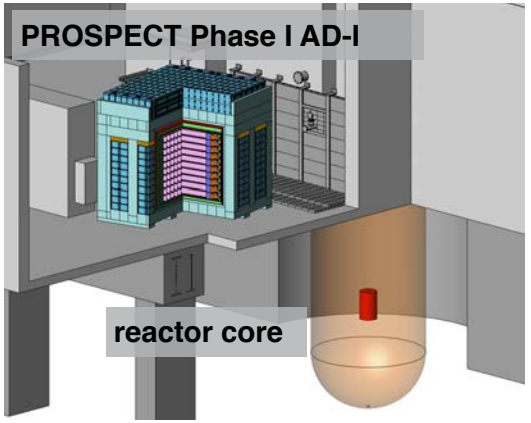
4x4 segments
1.2m length
400 liters
^{6}LiLS



PROSPECT AD-I
Physics measurement
Late 2016

10x12 segments
1.2m length
~3 tons
^{6}LiLS

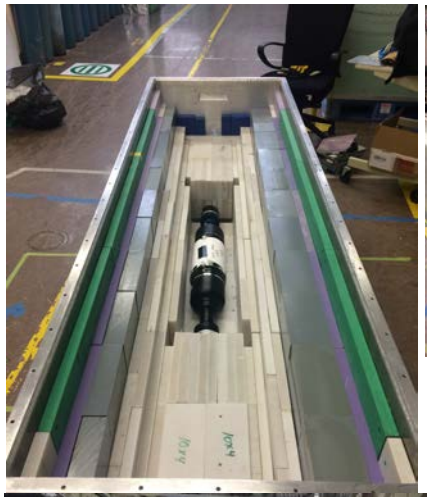




**Technically ready to proceed directly to near detector with available funding*

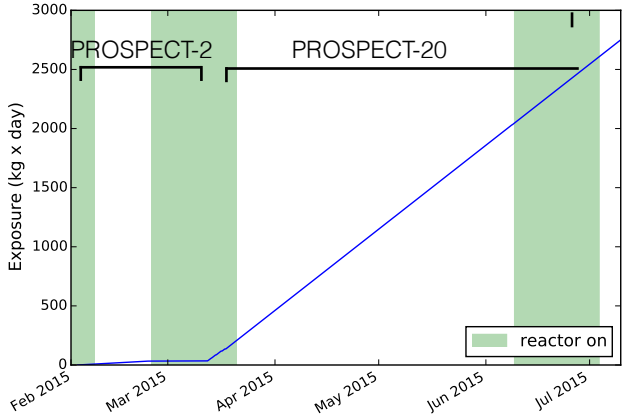
Validation of Monte Carlo from HFIR Data

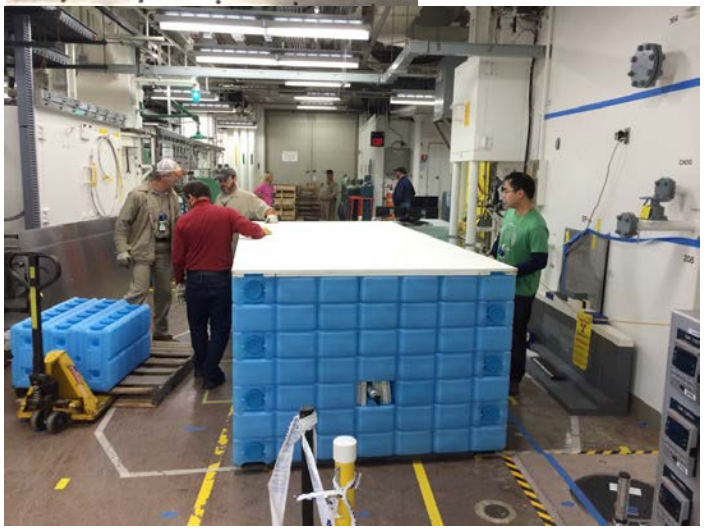
Monte Carlo Validation from operating multiple prototypes at HFIR site

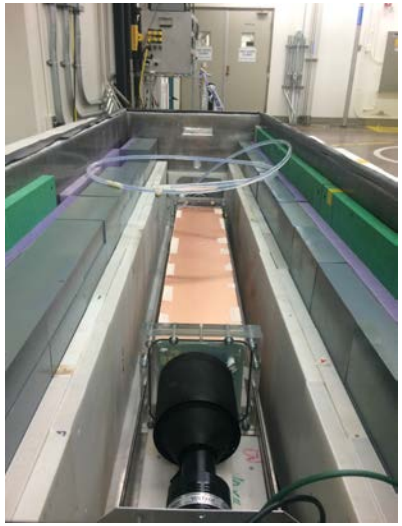


PROSPECT-2

operation and combined exposure

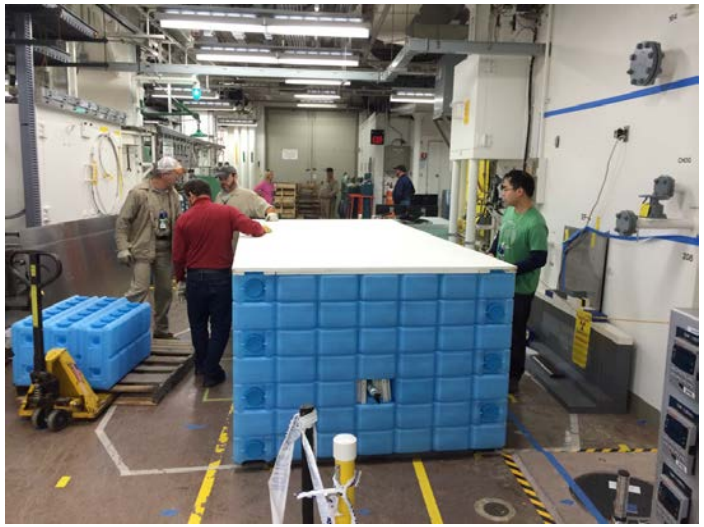


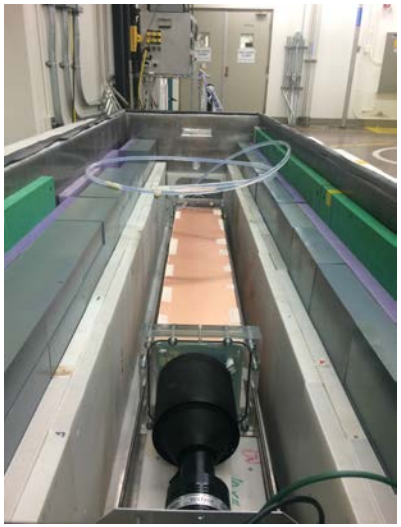




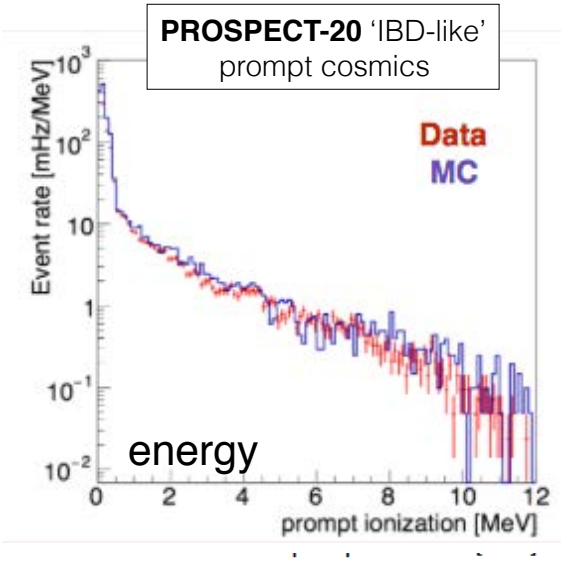
PROSPECT-20

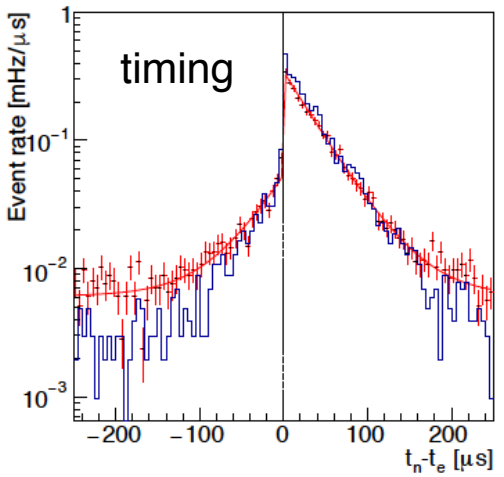
Validation of Monte Carlo from HFIR Data





PROSPECT-20 at HFIR



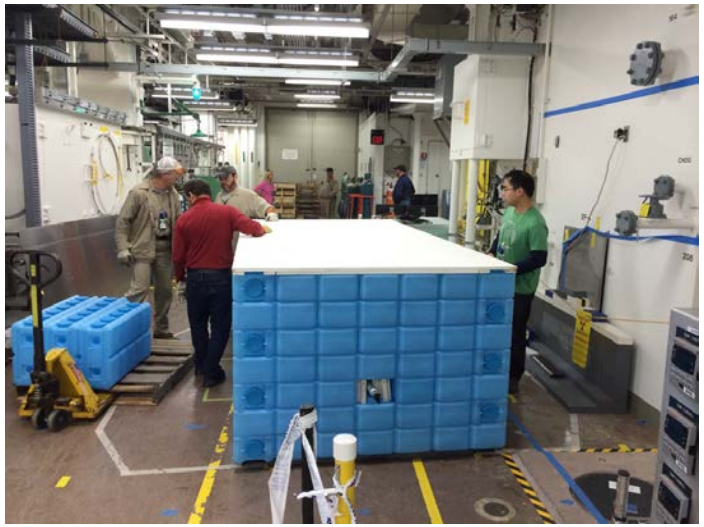


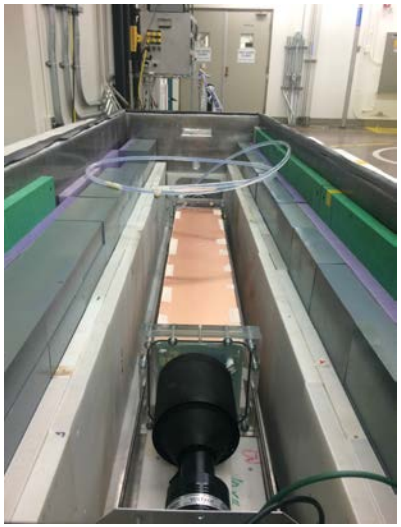
- PROSPECT-20 measured cosmic backgrounds during reactor-off
- PROSPECT-20 'simple' Monte Carlo agrees well with data

- confident in extrapolating MC to Phase I detector
- after series of effective cuts, can reach S:B > 3:1
- surpasses physics goals target
- will measure these backgrounds during reactor-off time in Phase I

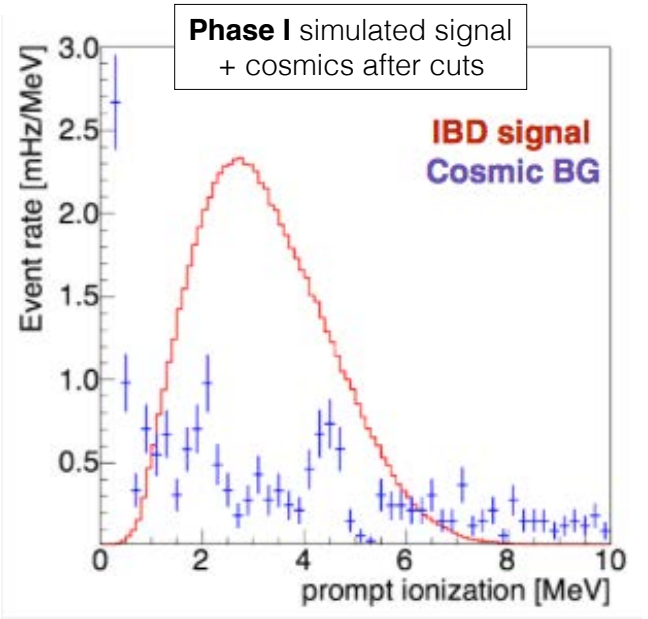
prototype deployment validated background Monte Carlo

Validation of Monte Carlo from HFIR Data





PROSPECT-20 at HFIR



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- confident in extrapolating MC to Phase I detector
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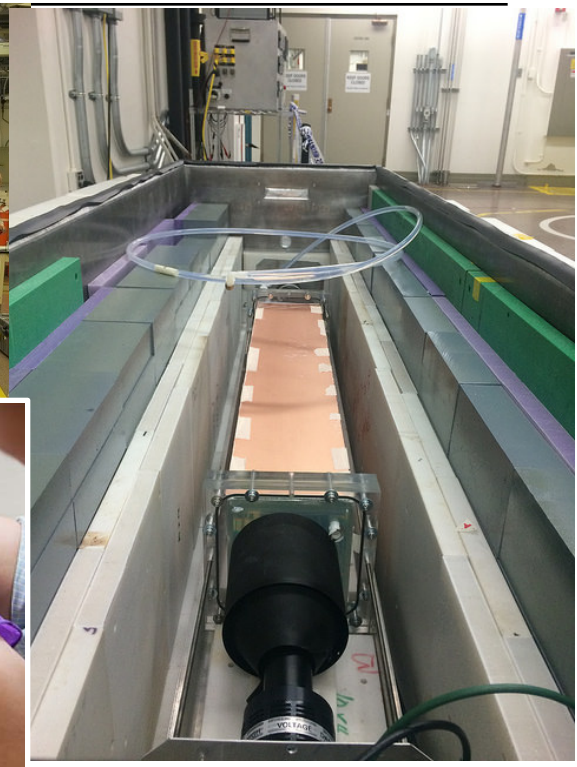
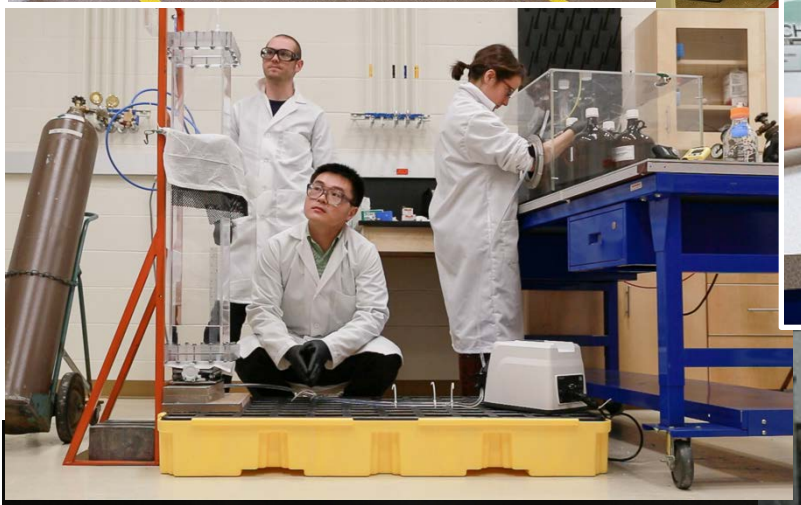
- surpasses physics goals target
- will measure these backgrounds during reactor-off time in Phase I

allows prediction of S:B for PROSPECT Phase I

PROSPECT R&D and Technical Activities





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PROSPECT Collaboration

Brookhaven National Laboratory
Drexel University
Illinois Institute of Technology
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University

site of experiment
High Flux Isotope Reactor, Oak Ridge National Laboratory

63 collaborators
13 institutions
3 national laboratories

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Summary

- New data are needed to address the existing reactor anomalies.

- PROSPECT Phase I will
  - Probe favored region of eV-scale sterile neutrinos at >3σ with 3 years of data.
  - Measure ^{235}U $\bar{\nu}_e$ spectrum, address spectral deviation, and provide new constraints on reactor antineutrino models complementary to current and future LEU measurements.
- PROSPECT R&D
  - Have developed LiLS detectors that can mitigate reactor- and cosmogenic related backgrounds.
  - Multiple detectors have been deployed at HFIR in preparation for full-size detector.
  - Completed R&D for technical verification and to mitigate technical, cost, and schedule risks.
- Ready to proceed with construction of Phase I.
- Data taking in 2017 with first physics results in 2018 possible.

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