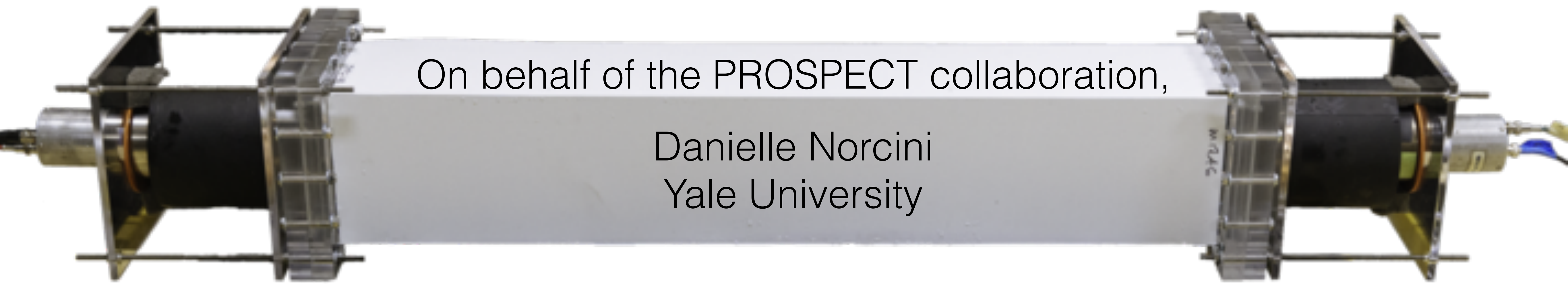
Development of PROSPECT detectors for precision antineutrino studies



On behalf of the PROSPECT collaboration,

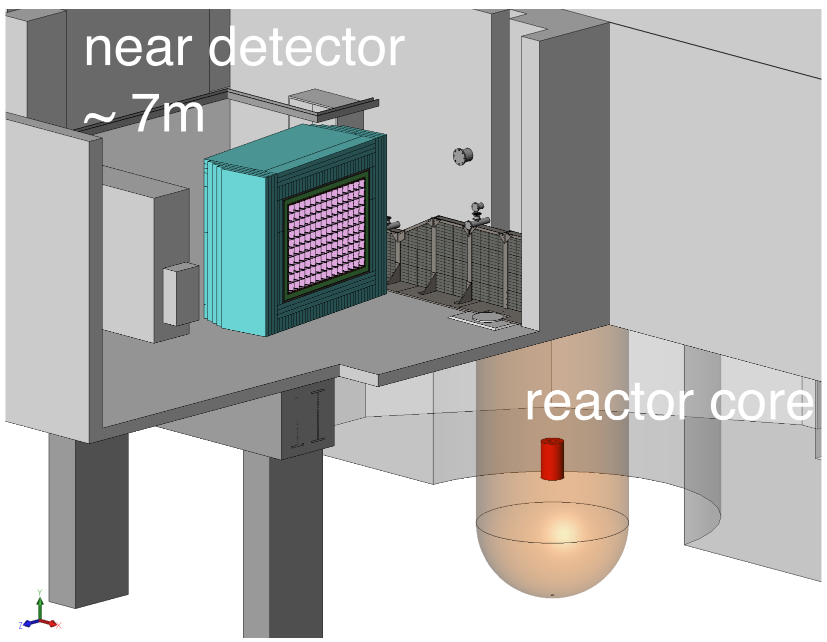
Danielle Norcini
Yale University

PROSPECT collaboration at DPF 2015:
K.Gilje - Neutrino - Aug 5 @7:00 - Sensitivity and discovery potential of PROSPECT

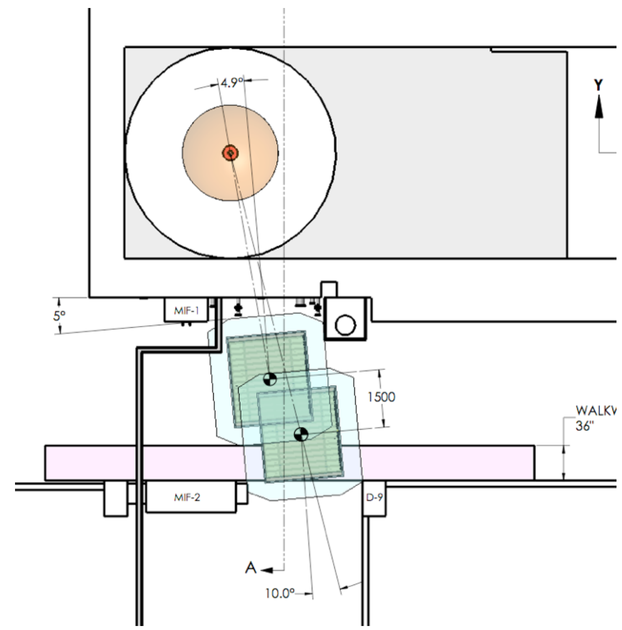
Precision Reactor Oscillation and SPECTrum experiment

Physics objectives:

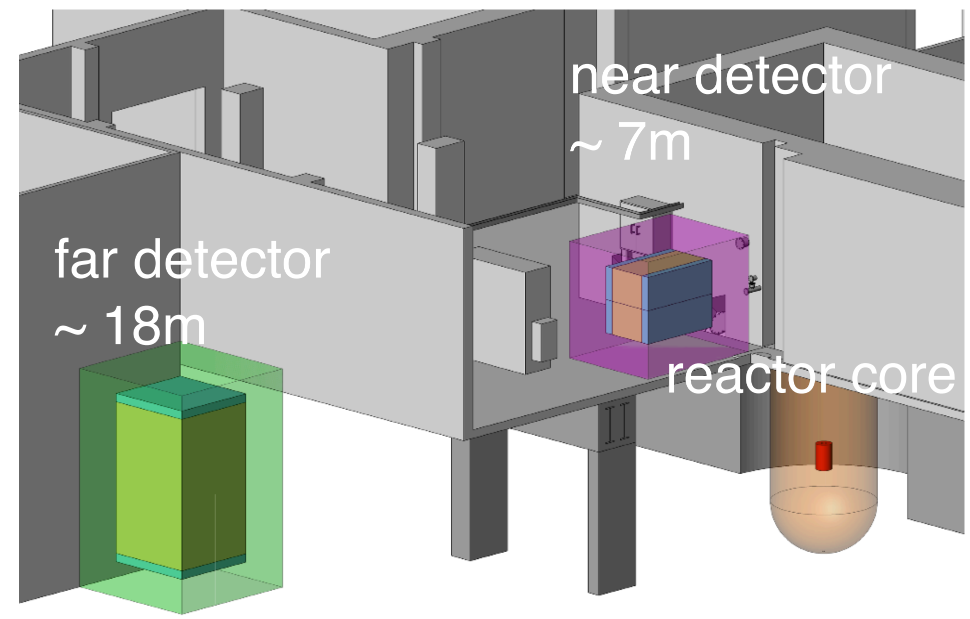
1. Precision measurement of ^{235}U reactor anti-ν_e spectrum
2. Search for short-baseline oscillation at distances <10m



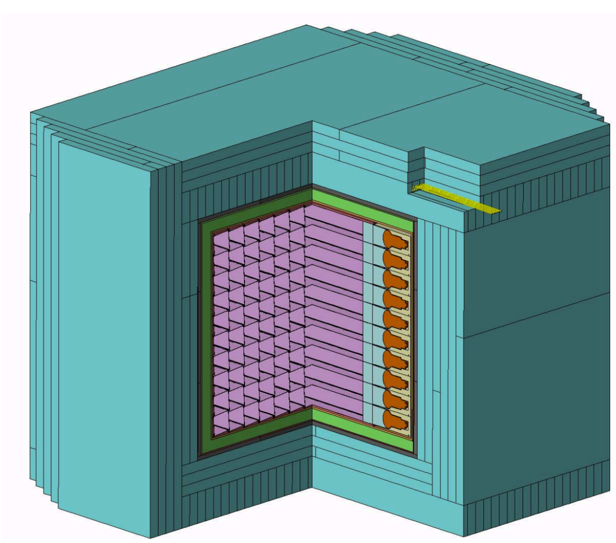
phase 1



phase 1+



phase 2



Phased approach:

- addresses experimental situation in a timely manner
- mitigates risks
- systematic control and increased physics reach
- allows collaboration to stay nimble and response to results from phase 1, expand only as needed

PROSPECT Phase 1 Detector

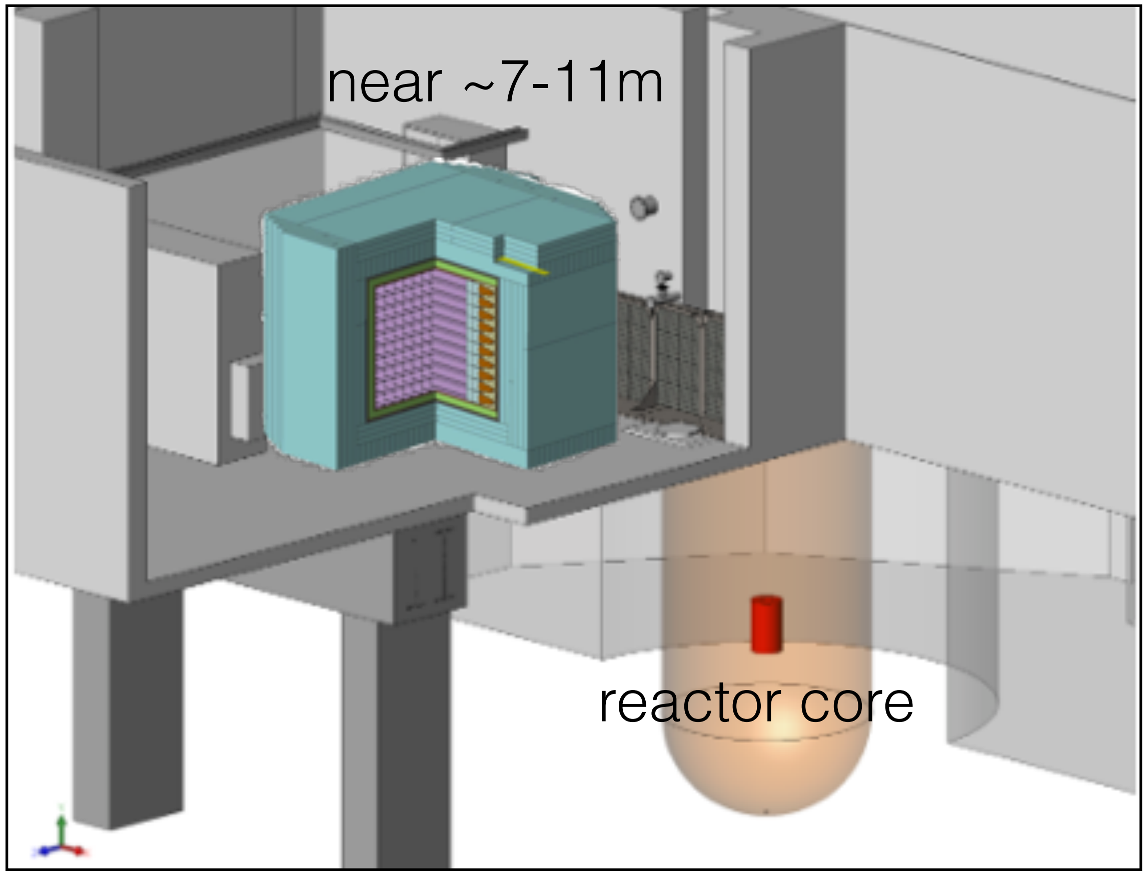
Physics goals:

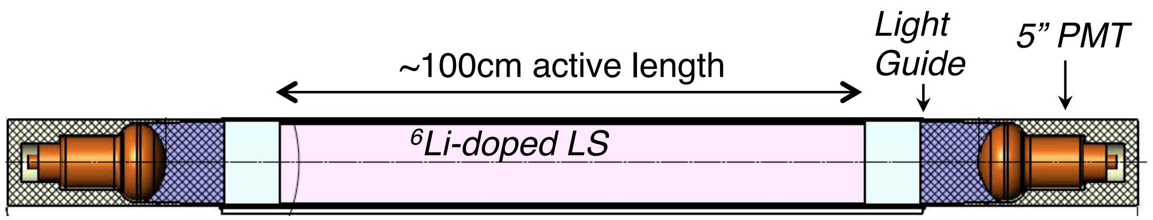
- probe sterile ν parameter space at 3σ in 1 calendar year
- precision measurement of ^{235}U neutrino spectrum

Phase 1 near detector:

- 2.5 tons ^{6}Li-loaded liquid scintillator
- ~10x14 segmented array with low-mass optical separators
- double-ended PMT readout
- movable, baseline coverage 7-11m

High Flux Isotope Reactor (HFIR)



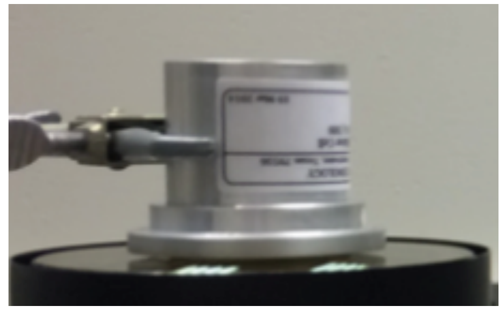


Near-surface detection challenges:

- cosmogenic + reactor backgrounds
- reduction techniques
  1. multi-layer shield to suppress n,γ
  2. time correlated β+n signal from IBD
  3. particle ID from Pulse Shape Discrimination
  4. segmentation allows for identification of spatially coincident signals and fiducilization

Phased detector development approach

PROSPECT-0.1 Y,H
Aug 2014
Spring 2015
Characterize LS



5cm
0.1liter
LS, ^{6}LiLS

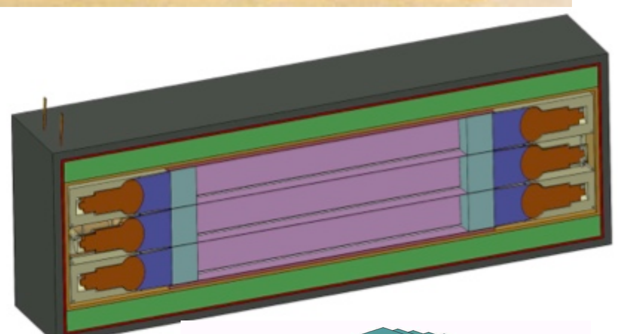
PROSPECT-2 Y,H
Winter 2014-15
Aug 2015
Background studies

12.5cm
1.7 liter
^{6}LiLS

PROSPECT-20 Y,H
Spring -Summer 2015
Characterize segment

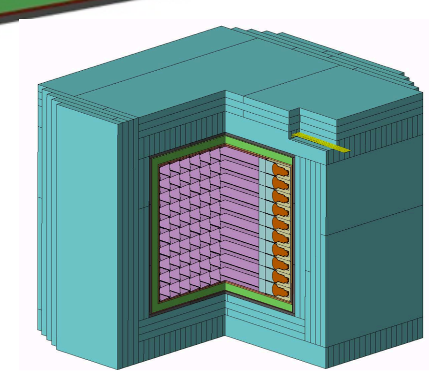
1m
23 liter
LS, ^{6}LiLS

PROSPECT-Nx20 H
Late 2015*
Mechanical prototype

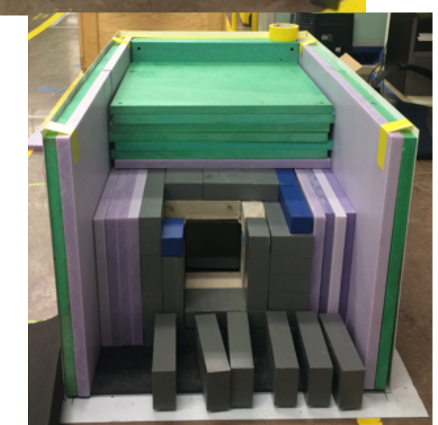


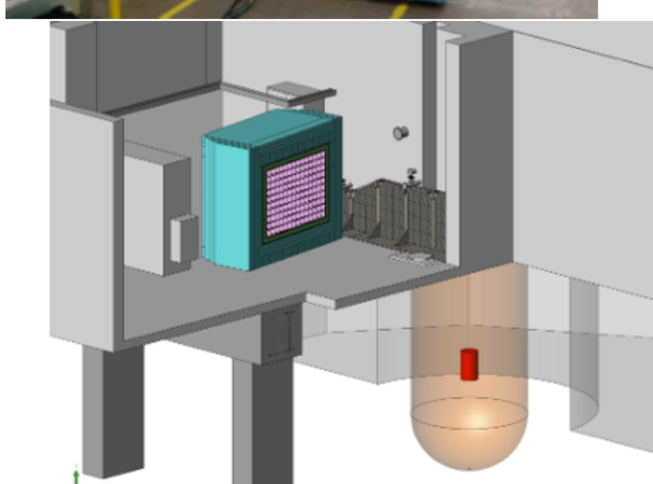
1m
Nx20 liter
^{6}LiLS segments

PROSPECT-2k H
Late 2016*
Physics measurement



1m
2.5 tons
^{6}LiLS segments



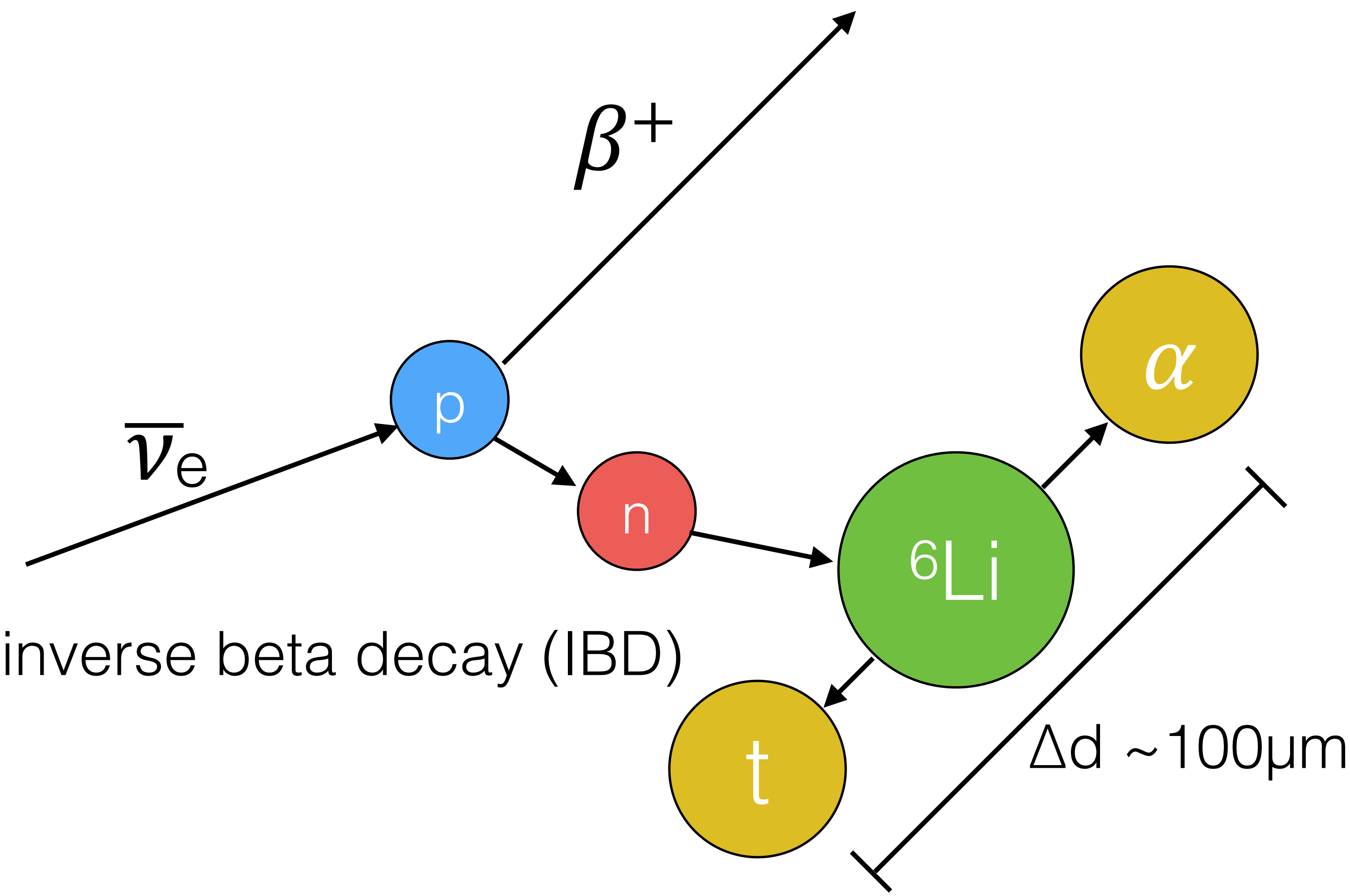


*technically driven schedule

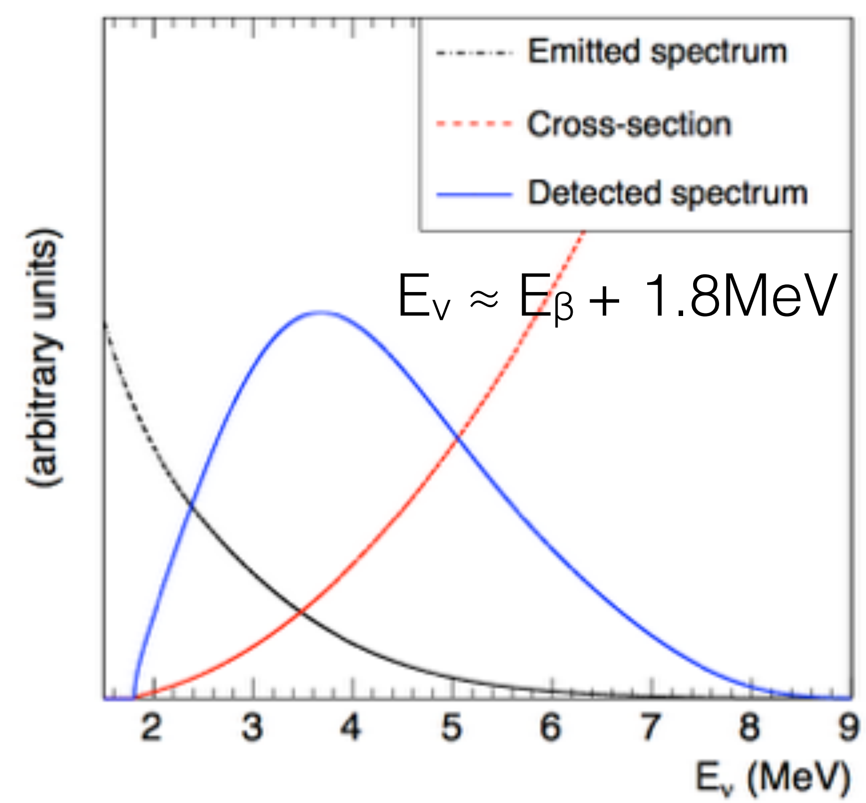
HFIR = H , Yale = Y

What are we looking for?

prompt ($t_0 = 0$): 1-10MeV annihilation



typical reactor spectrum



delay ($t_c = 40$μs): 0.6MeV_{ee} (n, ^{6}Li) capture

coincidence of these two signals indicates an IBD event

Major backgrounds at near-surface site

Correlated Backgrounds:

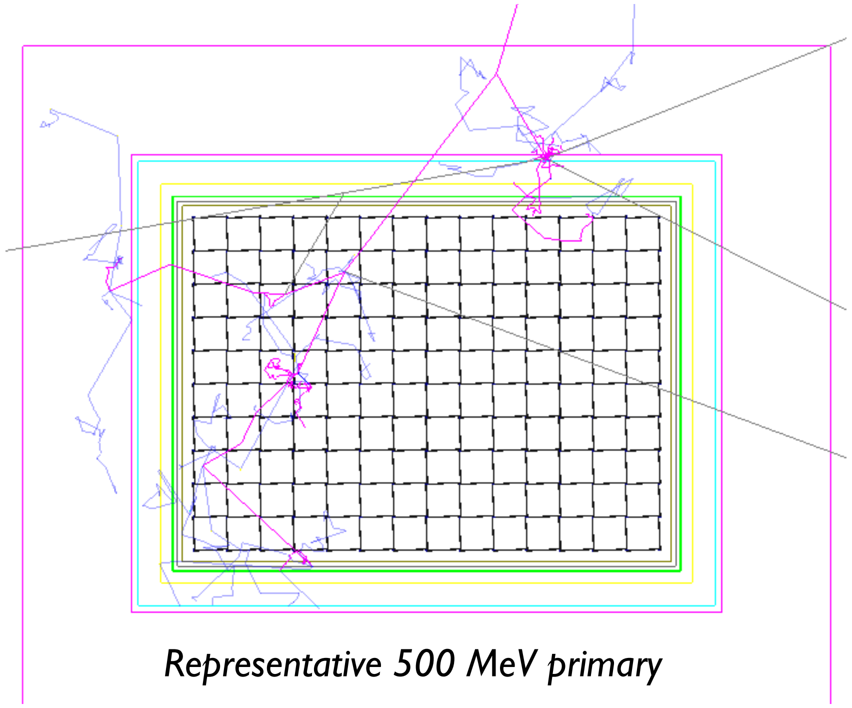
- cosmogenic fast neutrons (neutrons and muon-induced spallation)
- multiple neutron captures (cosmic showers)

Uncorrelated Backgrounds (accidental):

- reactor-related gammas or gammas from internal backgrounds (^{232}Th, ^{40}K)

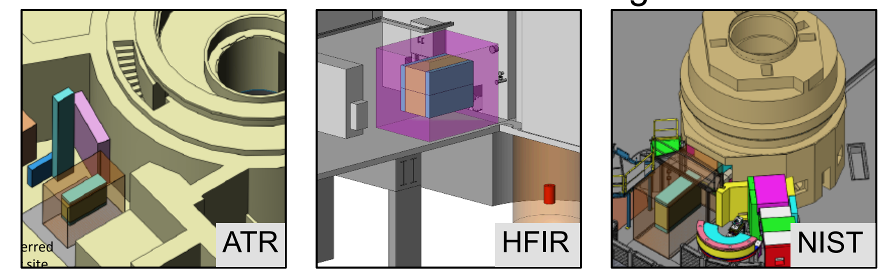
Signal	inverse beta decay γ-like prompt, n-like delay
Background	fast neutron n-like prompt, n-like delay
	accidental gamma γ-like prompt, γ-like delay

Phase 1 cosmic neutron event

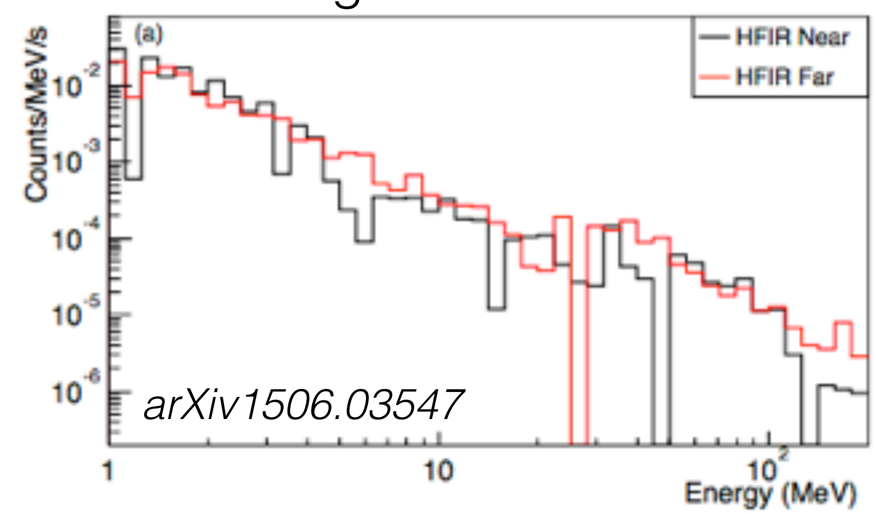


Site background characterization at HFIR

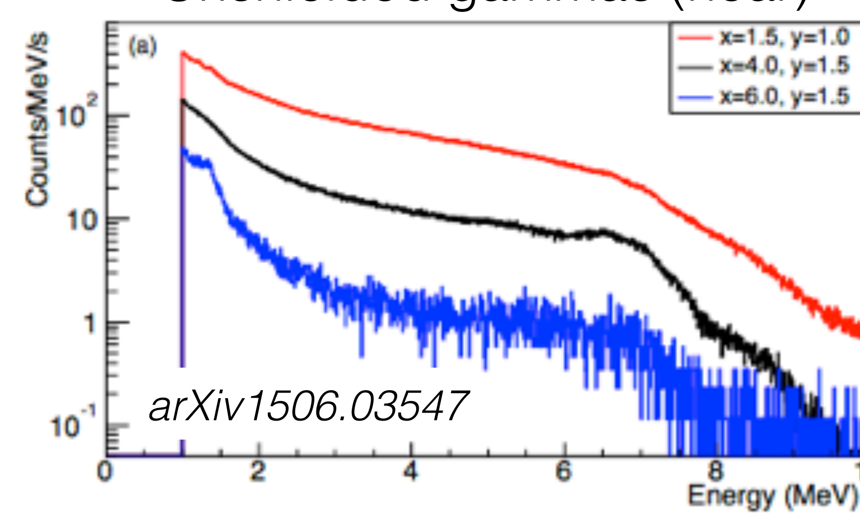
Detector Locations and Logistics



Cosmogenic fast neutrons



Unshielded gammas (near)



- conducted detailed evaluation at 3 high power HEU reactors (ATR, HFIR, NIST)
- characterized sources and distribution of reactor and cosmogenic background
- all sites viable for PROSPECT
- HFIR selected for operation schedule and logistics

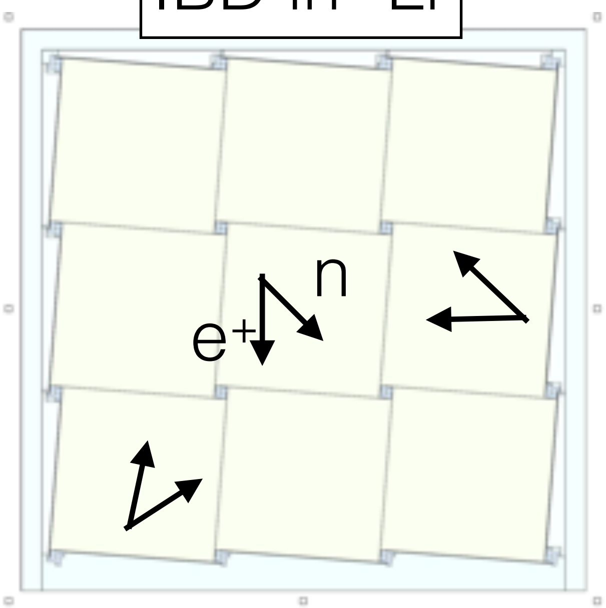
Detailed in paper:
PROSPECT collaboration, *Background Radiation Measurement at High Power Research Reactors* (*arXiv1506.03547*).

established feasibility by completing exhaustive assessment and selected HFIR

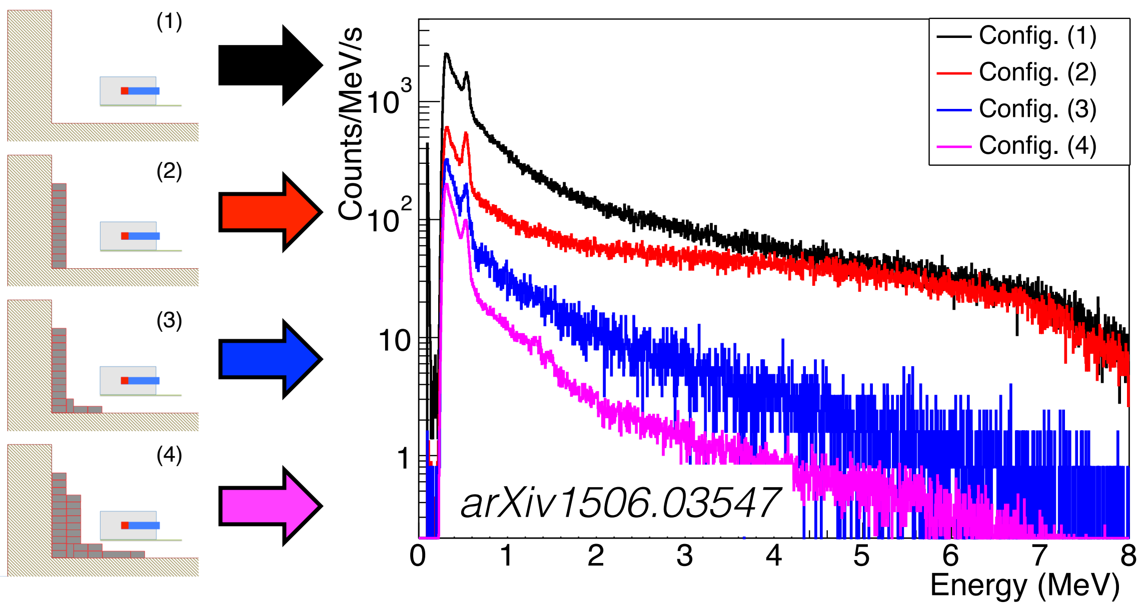
Tackling backgrounds with detector design

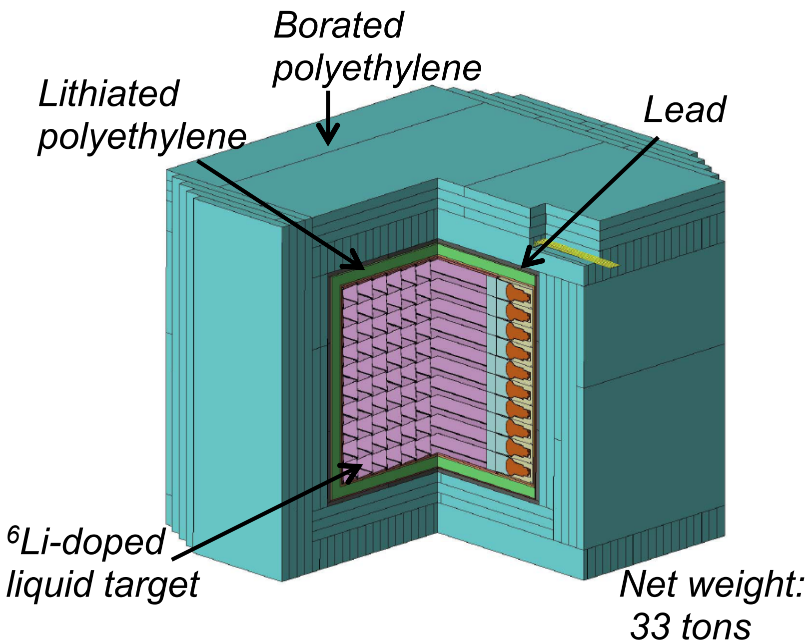
- the neutron capture on ^{6}Li allows for event localization, and combined with the localized e^+ gives a spatial correlation in addition to the IBD temporal correlation
- easy fiducialization to control gamma backgrounds
- designed localized shielding to suppress cosmogenic and reactor correlated backgrounds

IBD in ^{6}Li



effect of increasing lead wall on gammas

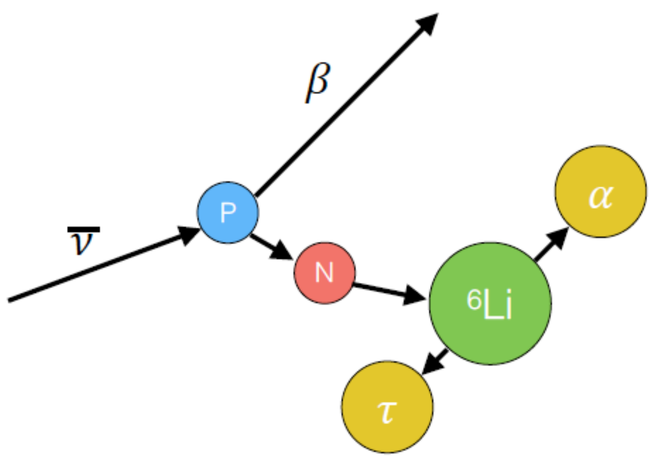




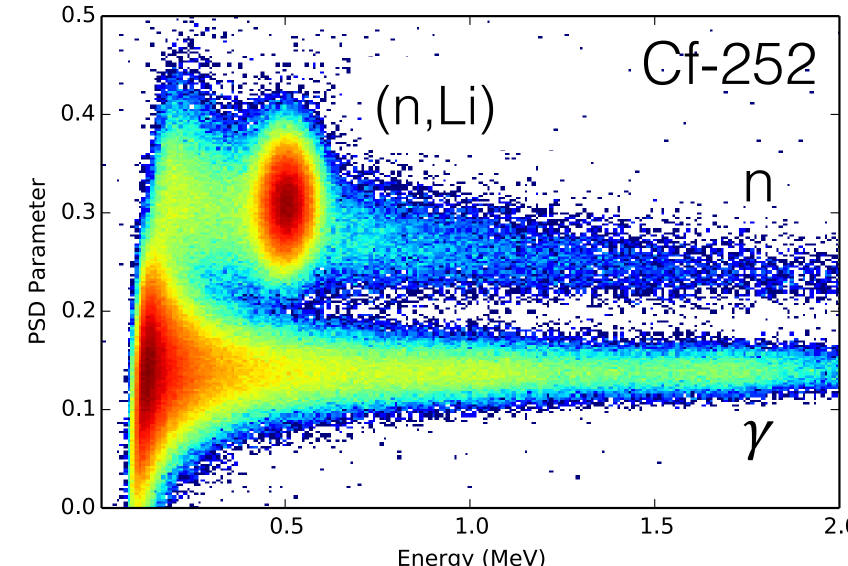
detector structure and passive shielding designed for near-surface backgrounds

Tackling backgrounds with PSD

Pulse Shape Discrimination (PSD) will provide important particle identification information.

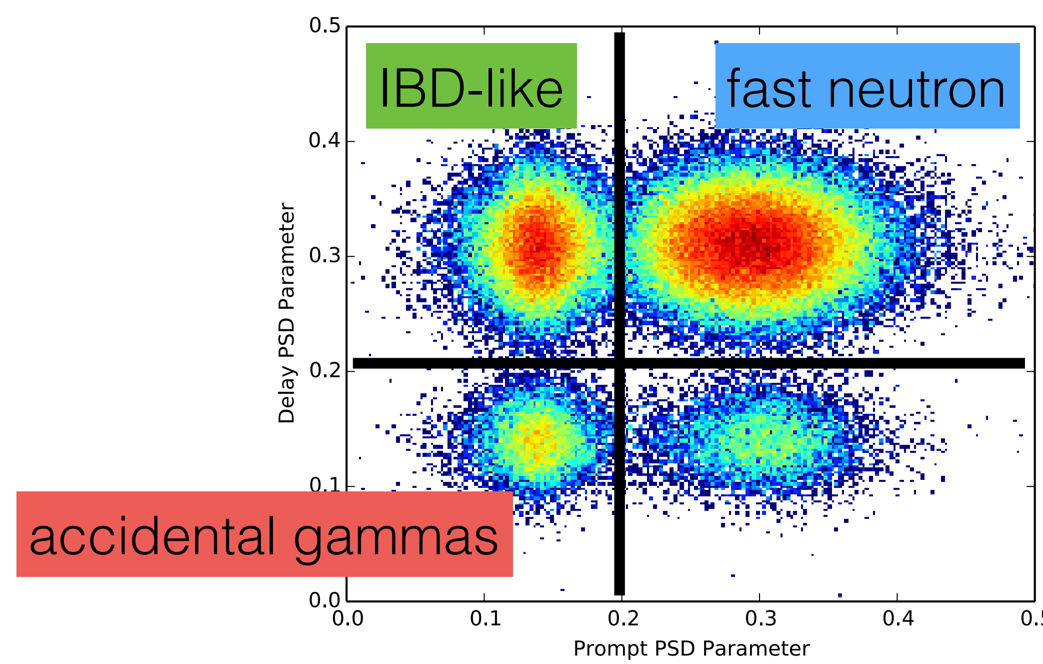


prompt signal: 1-10 MeV positron from inverse beta decay	
delay signal: 0.6 MeV signal from neutron capture on ^{6}Li	



arXiv1309.7647

PROSPECT-2 (LiLS)



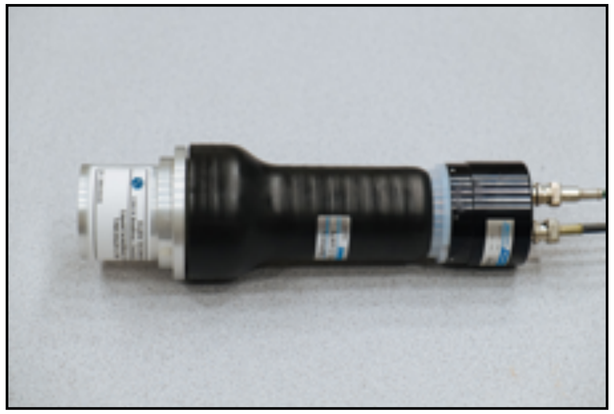
PSD signatures	
Signal	inverse beta decay γ-like prompt, n-like delay
Background	fast neutron n-like prompt, n-like delay
	accidental gamma γ-like prompt, γ-like delay

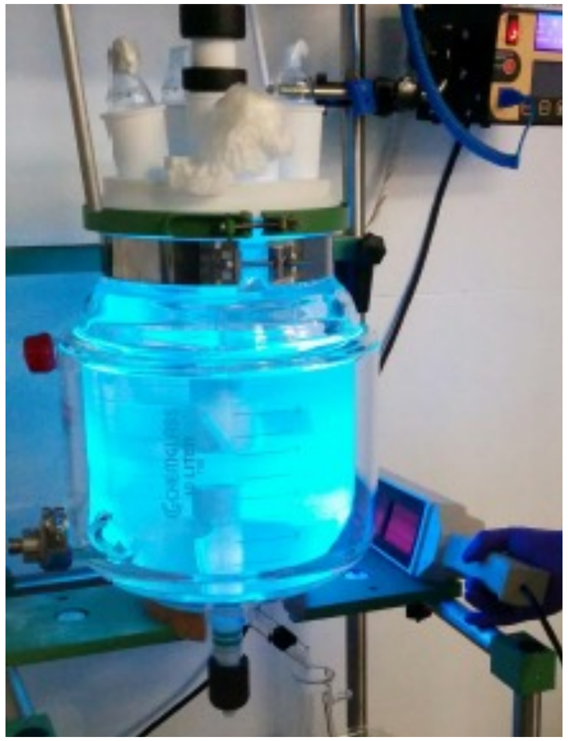
particle ID strongly suppresses cosmogenic correlated and reactor-induced uncorrelated backgrounds

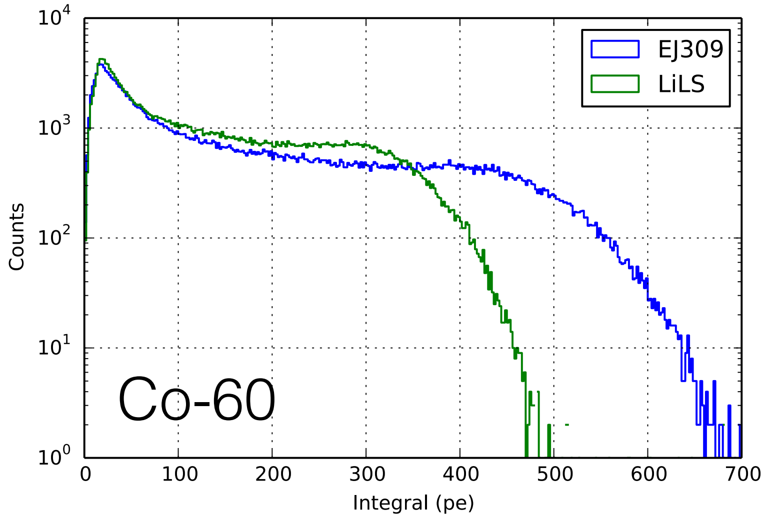
Liquid scintillator (LS) development

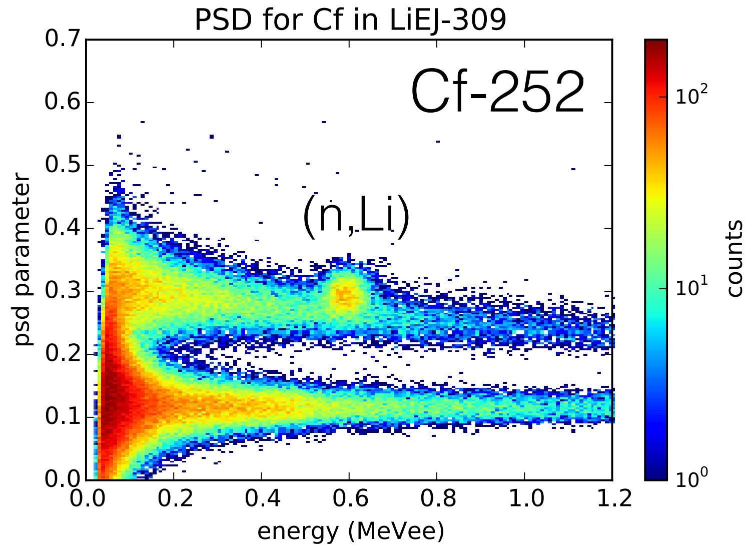
Scintillator specs (PROSPECT-0.1):

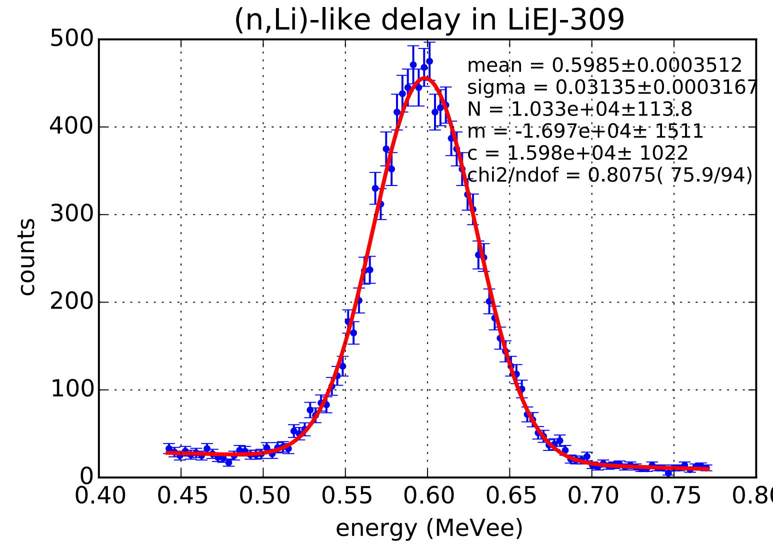
- Light Yield$_{EJ\text{-}309}$ = 11500 ph/MeV
- Light Yield$_{LiLS,\ measured}$ = 8200 ph/MeV
- prominent neutron capture peak in LiLS
- PSD FOM at (n, Li) is 1.79
- energy resolution (σ/E) of 5.2% at 0.6MeV$_{ee}$











developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities

Compatibility and design of low-mass separators

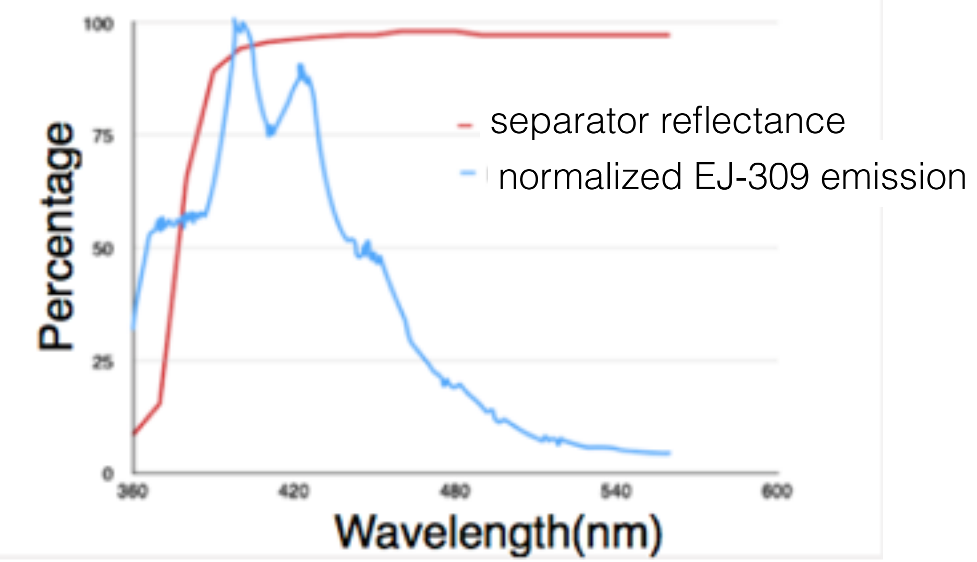
Compatibility:

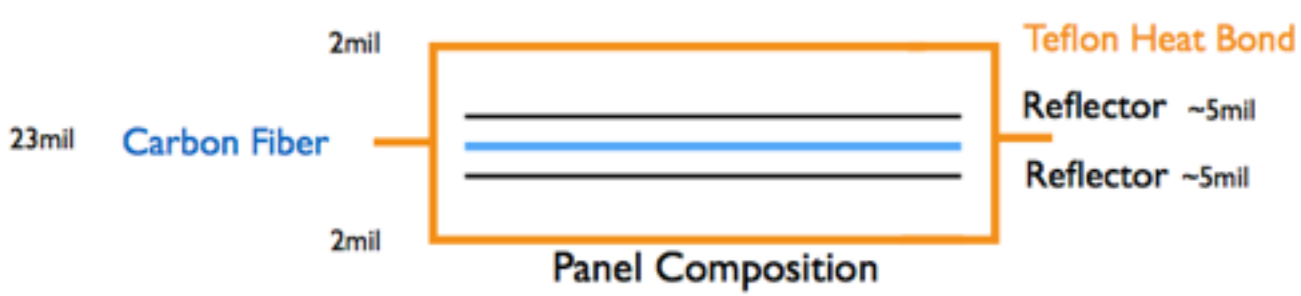
- extensive material compatibility testing required to ensure long-term LS performance
- focus on materials proven in recent experiments - PTFE, acrylic, polypropylene, …
- long-term mechanical stability verified

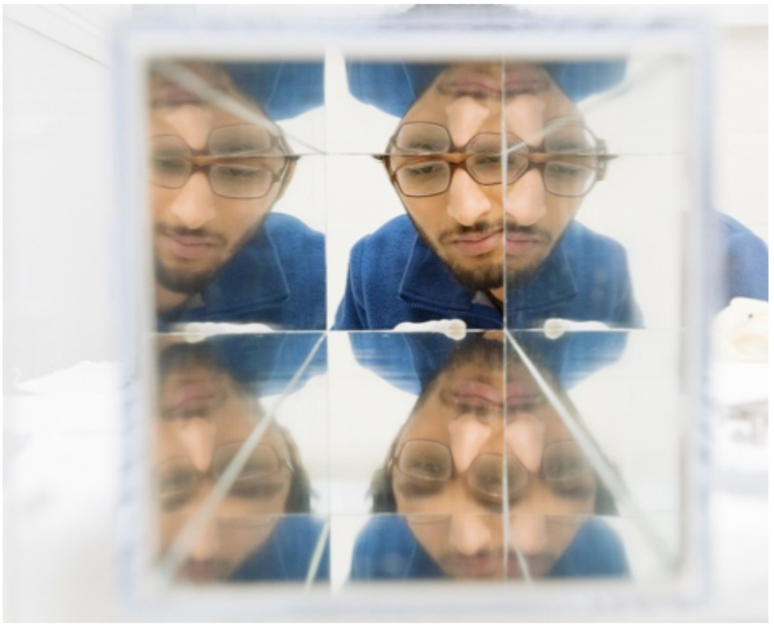
Separators:

- physics goals demand low inactive mass, high reflectivity, and long-term compatibility
- developed multi-layer system meeting all requirements
- fabrication procedures for full-scale system under validation

separator reflectance vs wavelength



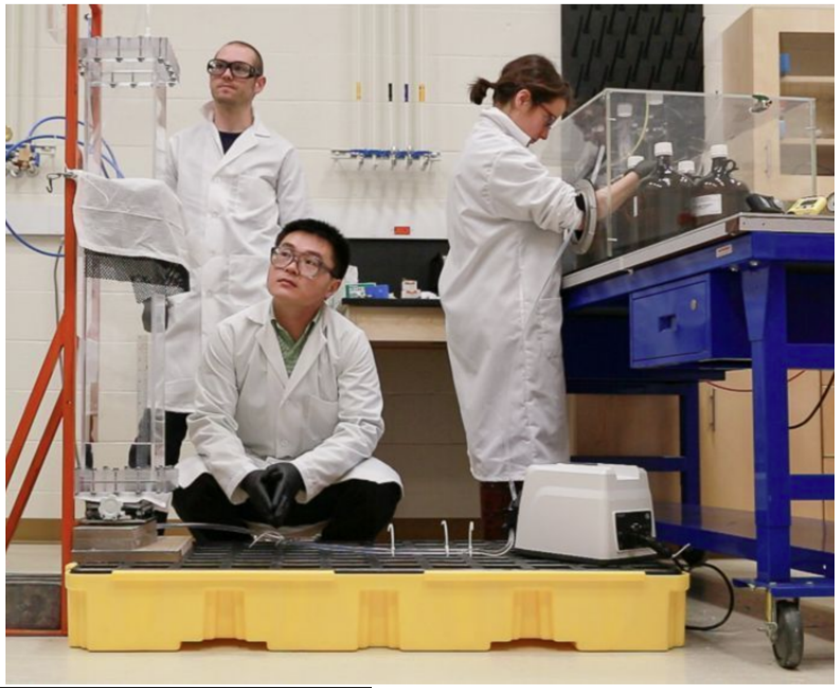


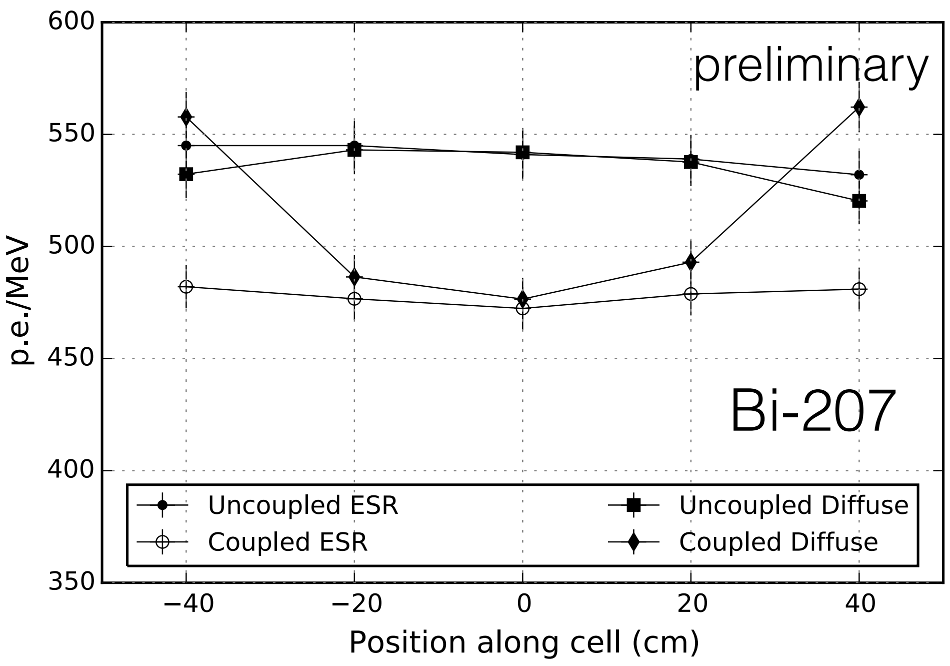


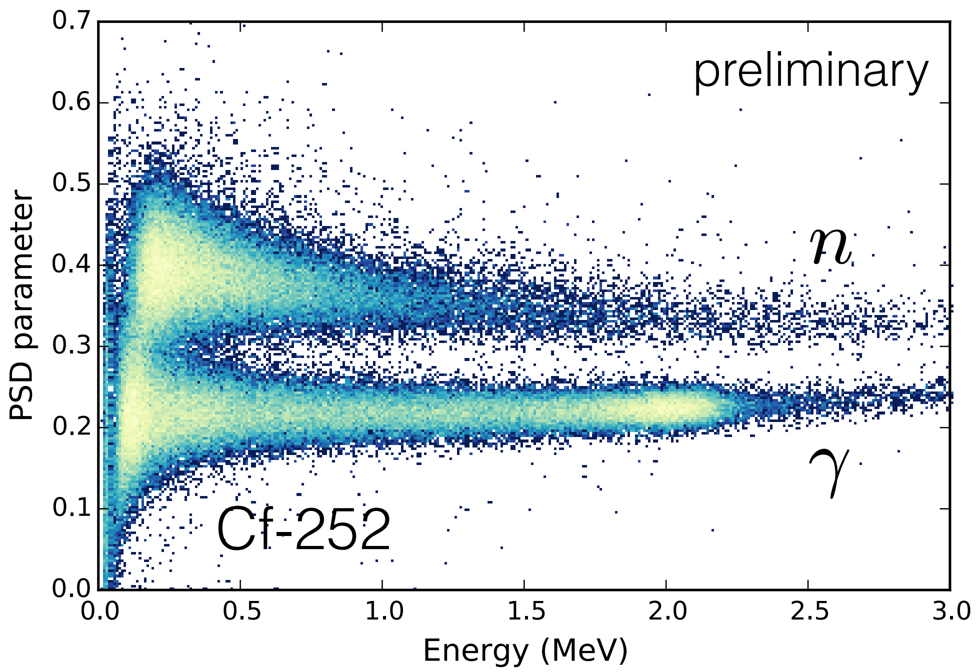
Low-mass reflector prototypes

produced robust separators with good reflectivity from LS-compatible materials

Segment response: light collection and PSD studies





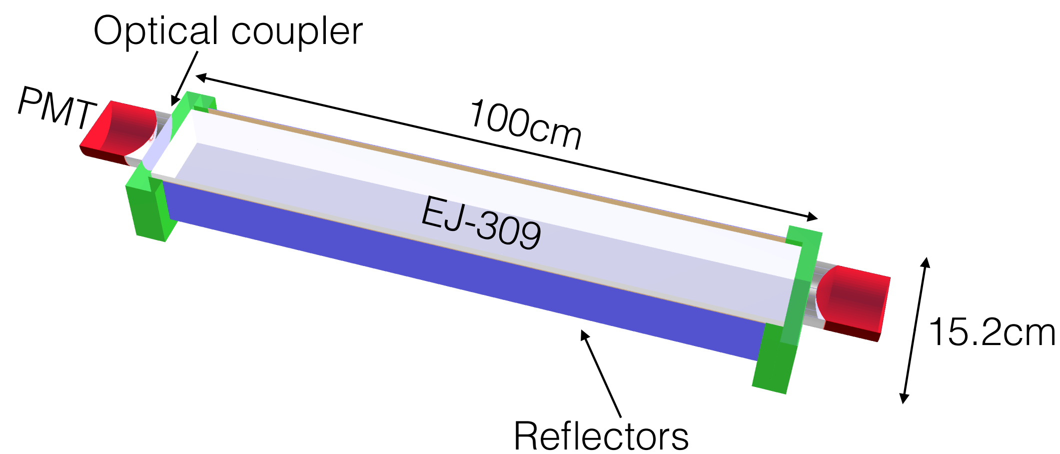


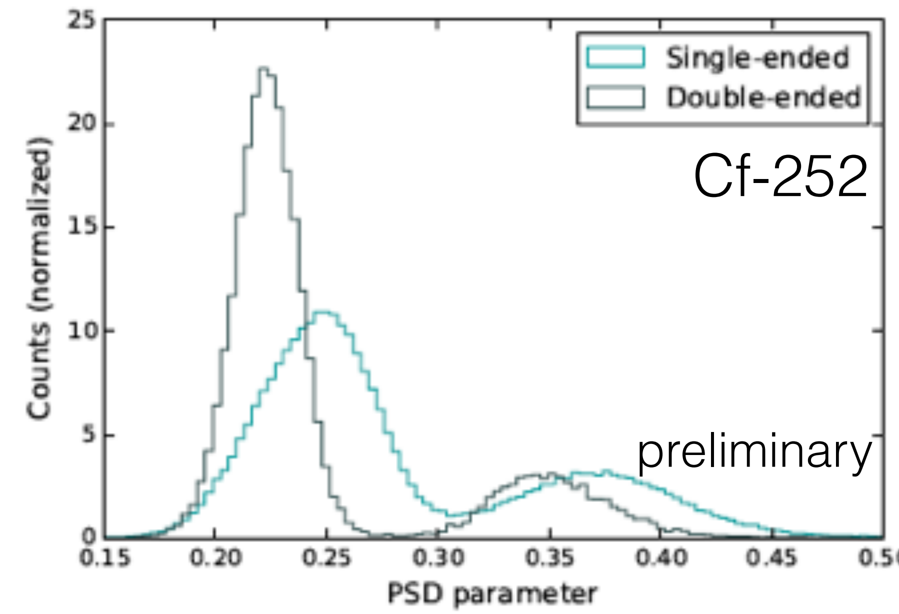
PROSPECT-20atYale (EJ-309):

- optimize collection, PSD with air-coupled specular separators (external)
- average light collection: 527± 10 photoelectrons/MeV
- low energy PSD (0.5-0.7MeV) allows for 99.99% rejection of γ, 99% acceptance n events
- detailed technical paper forthcoming

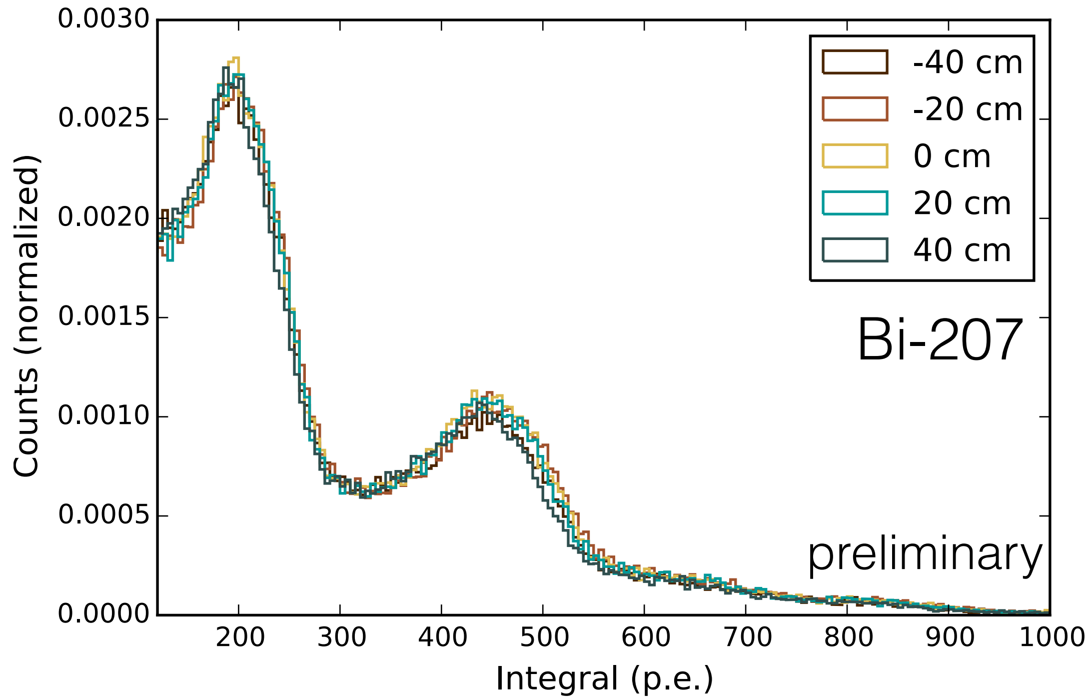
excellent PSD is obtained in realistic geometry at target light collection of 500pe/MeV

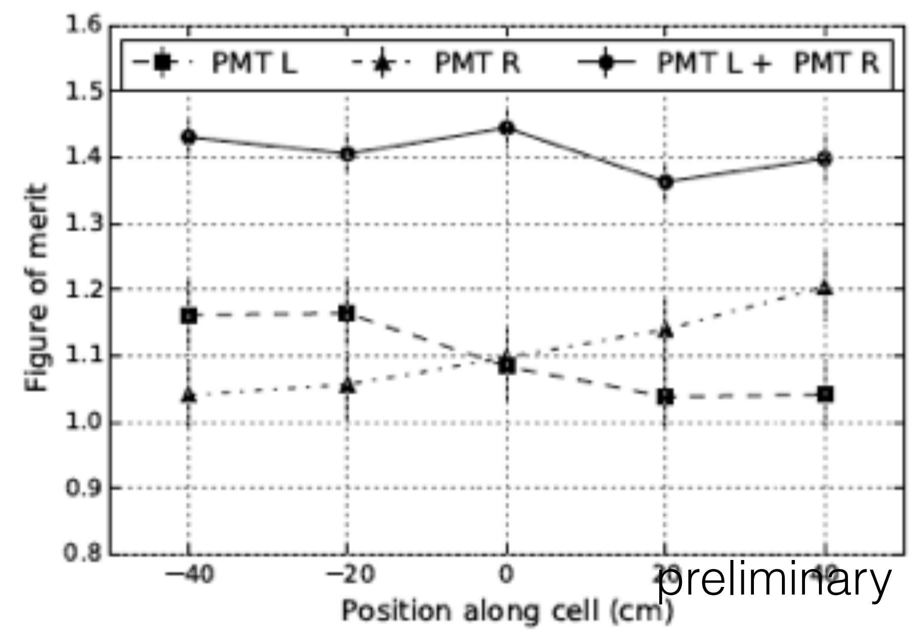
Segment response: double-ended readout





Collection from sum of 2 PMTs





double-ended readout allows for uniform optical collection, enhanced PSD, and axial position resolution

Simulation to benchmark prototype data

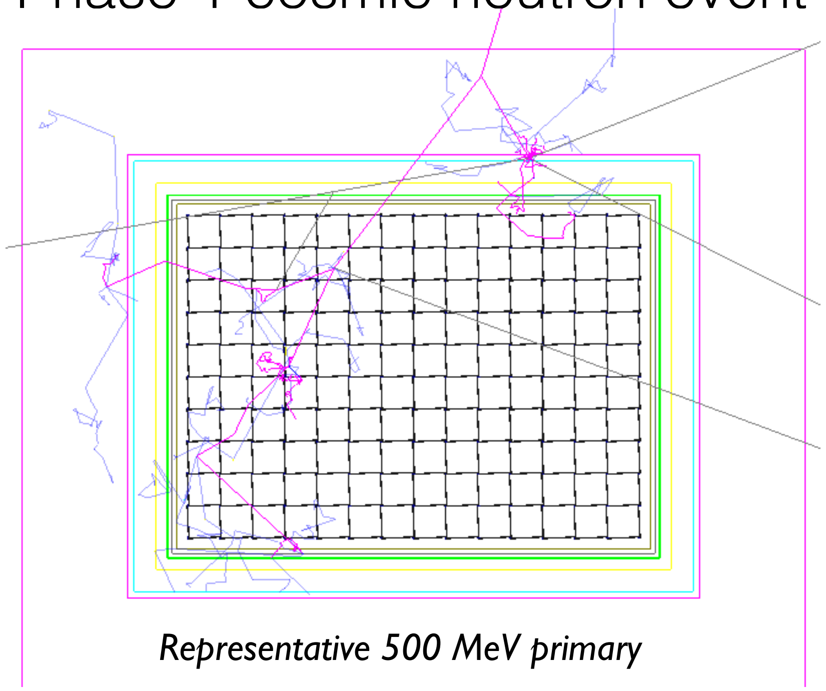
Simulations have been developed to meet distinct needs:

1. **Background mitigation**
   develop single flexible Monte Carlo, benchmark against prototypes, enable extrapolation to full detector

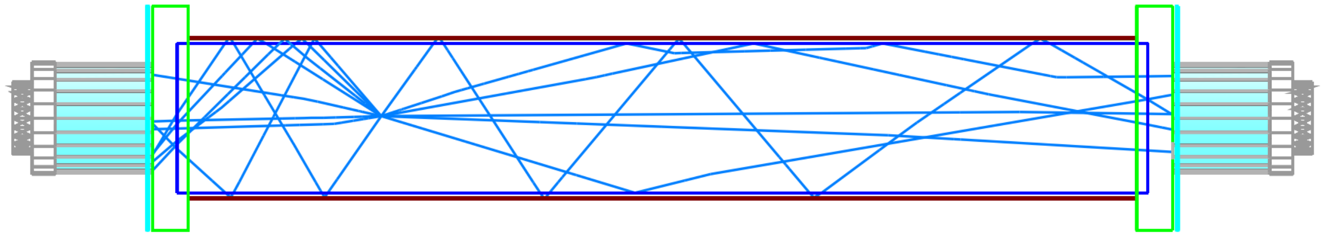
2. **Detector response**
   detailed model of detector response ensures PROSPECT has precision spectral measurement capability

3. **Design**
   simulations further used to optimize shielding, light transport, etc in context of science goals

Phase 1 cosmic neutron event



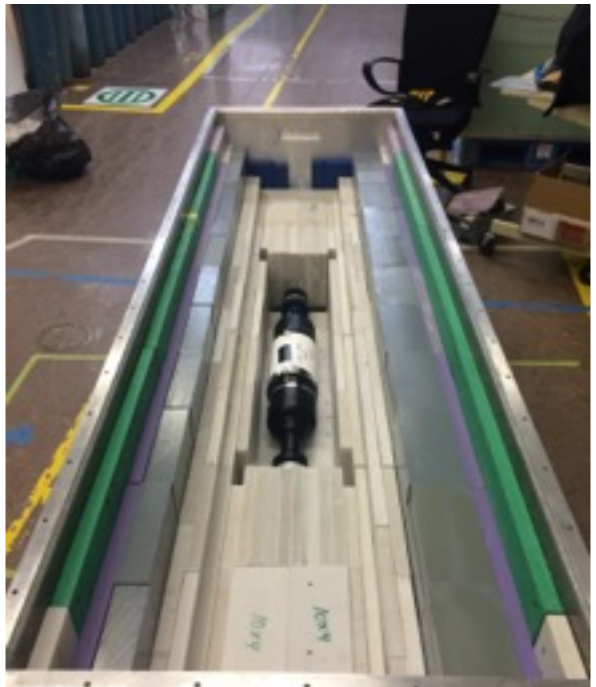
Representative 500 MeV primary



simulation of PROSPECT-20 with optical transport

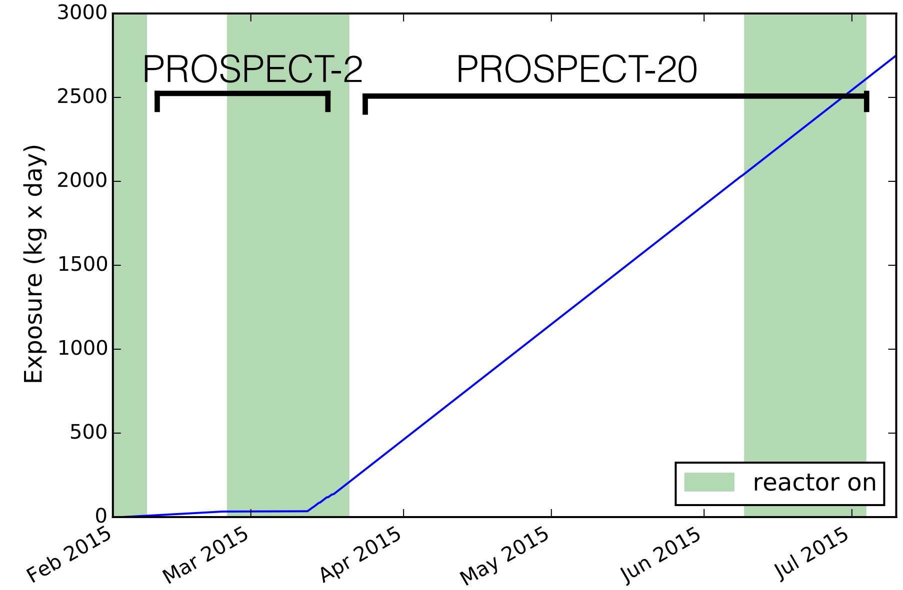
prototyping program has enabled validation of mechanics, detector response, and simulation models

Validation of MC from prototypes at HFIR site

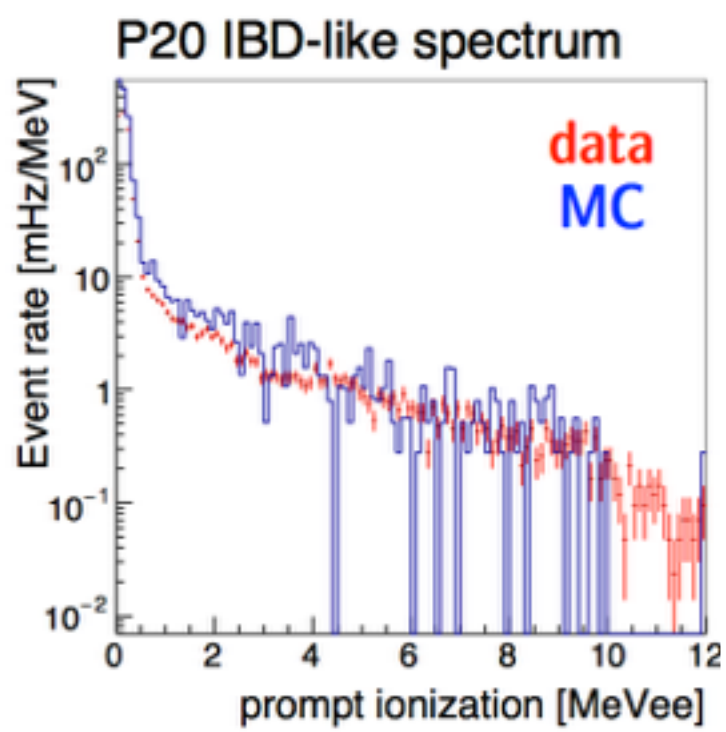


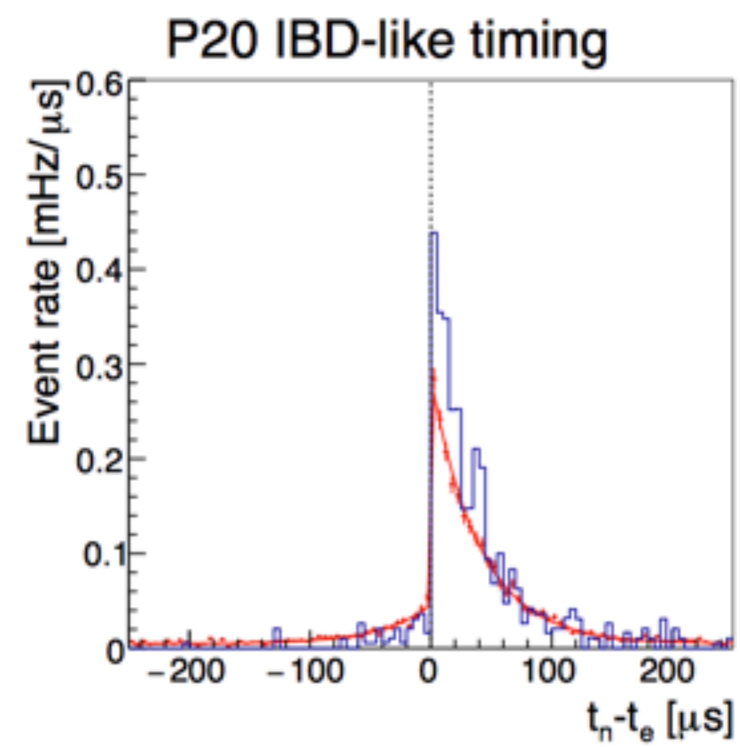
PROSPECT-2 at HFIR

combined exposure



PROSPECT-20 at HFIR



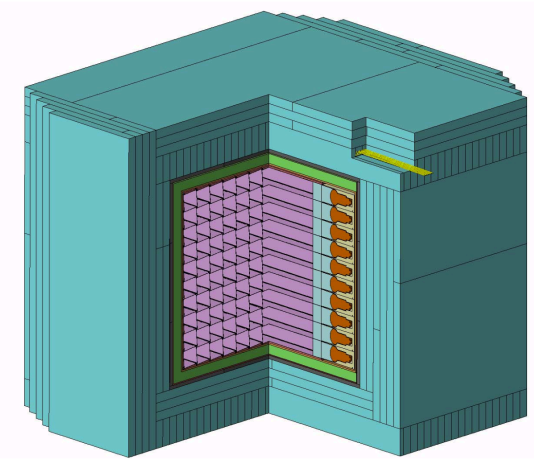


on-site prototype deployment verified operational interfaces and provided validation of background MC

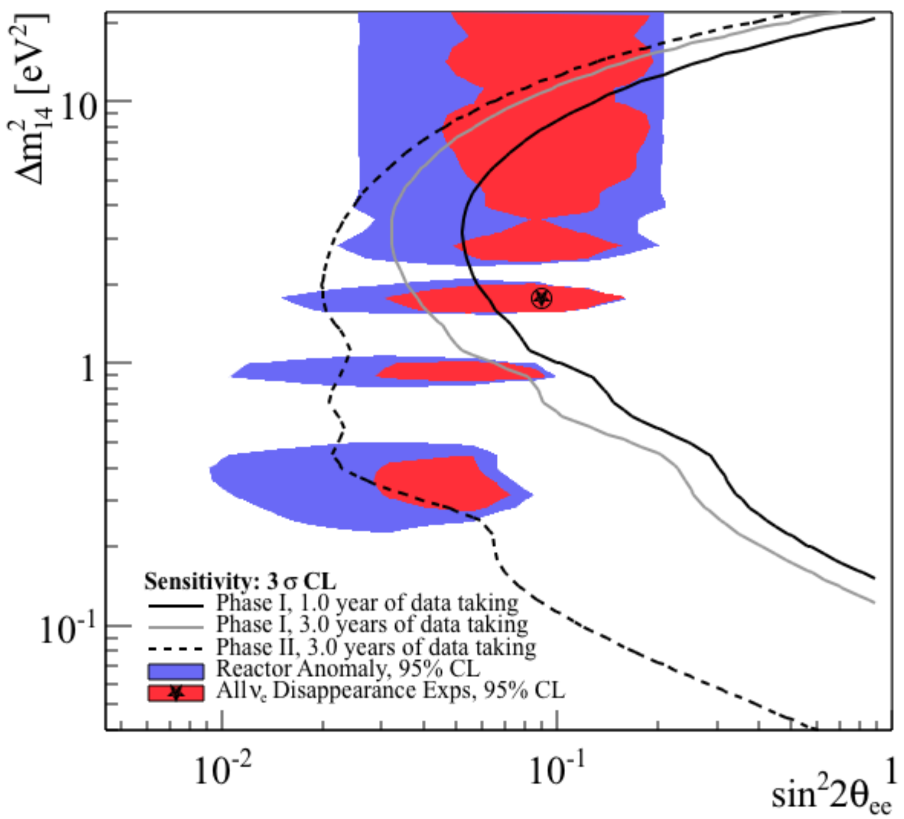
PROSPECT: Hands-on science

Next steps for PROSPECT

PROSPECT-20 at HFIR



PROSPECT Phase 1+2 sensitivity



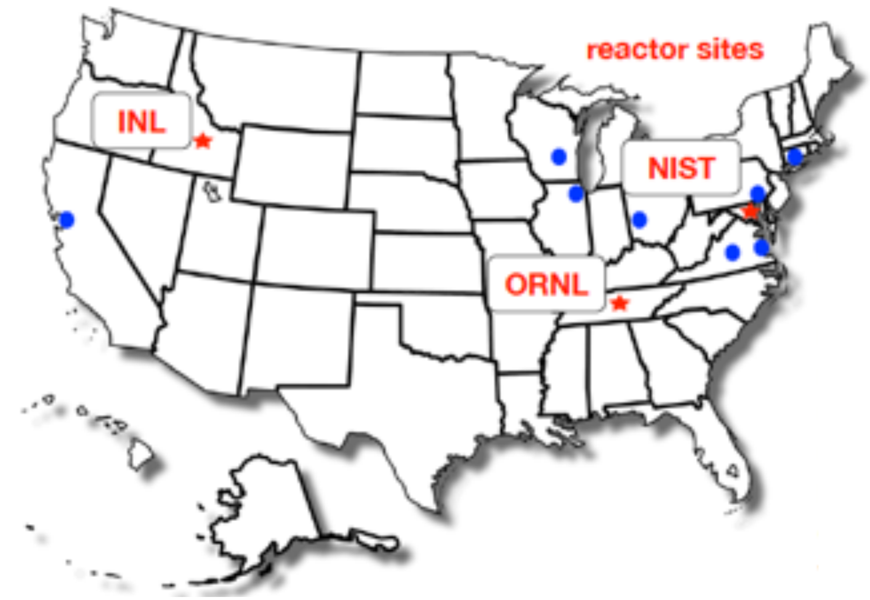
PROSPECT is ready to proceed with building the Phase 1 near detector at HFIR.

Concluding statements

1. PROSPECT Phase 1 is ready to proceed with precision ^{235}U spectrum measurement and short baseline oscillation search.

2. The PROSPECT R&D program has:
   - successfully **deployed multiple prototype detectors** to valididate detector performance and simulation models, as well as establish on-site operational procedures
   - developed a **detailed understanding of near-surface backgrounds** at research reactor facilities, including HFIR, as well as background mitigation techniques
   - **developed technology required for the Phase 1** detector: Li-doped liquid scintillator, low-mass separators, and segment design that optimize light collection, PSD, and uniformity
   - **produced simulation models** validated against prototype data that allow reliable predictions of Phase 1 detector performance

The PROSPECT Collaboration



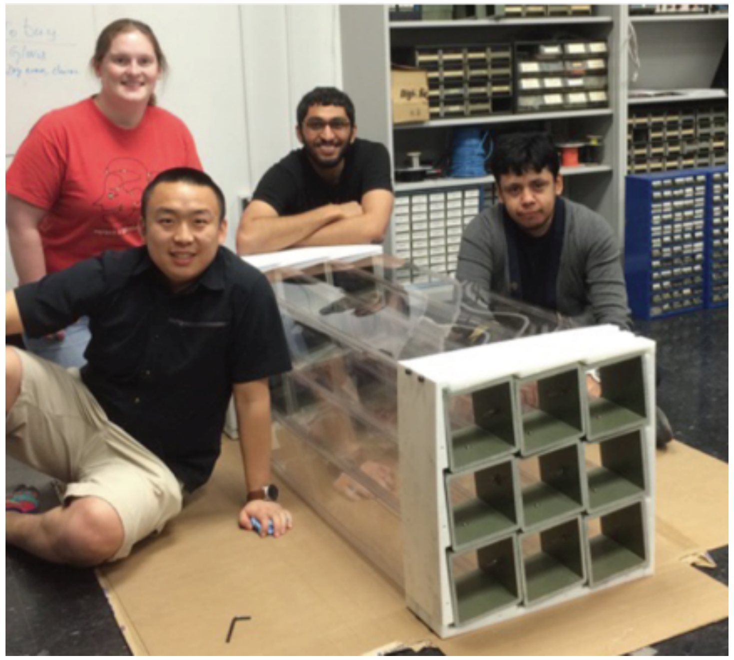
Brookhaven National Laboratory
Drexel University
Illinois Institute of Technology
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
University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

3 reactor sites | 5 national laboratories | 9 universities | 63 collaborators

prospect.yale.edu

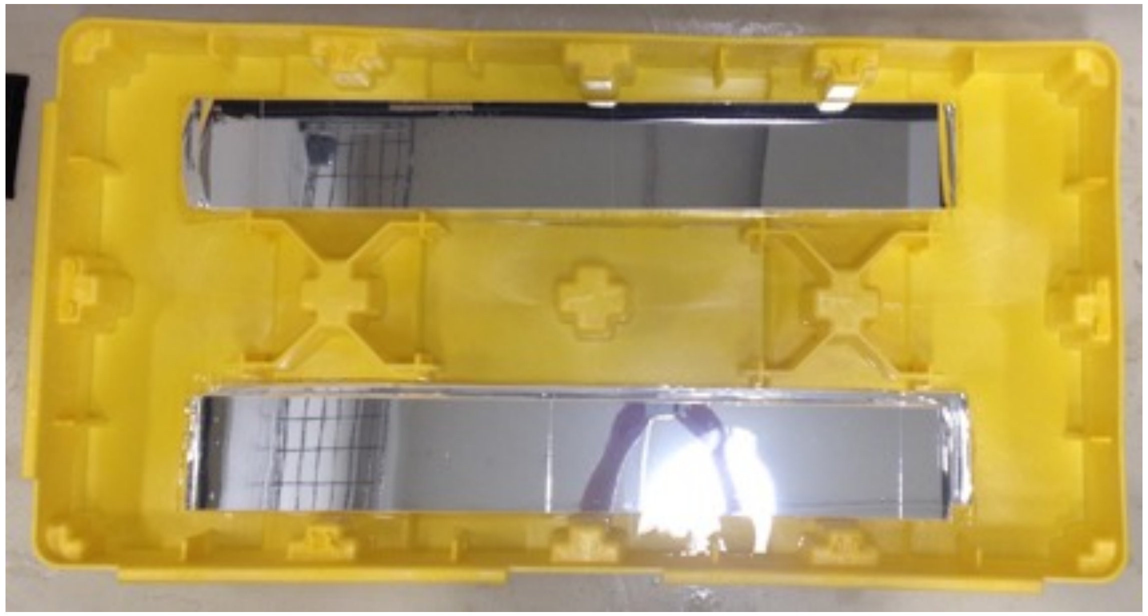
Current PROSPECT work

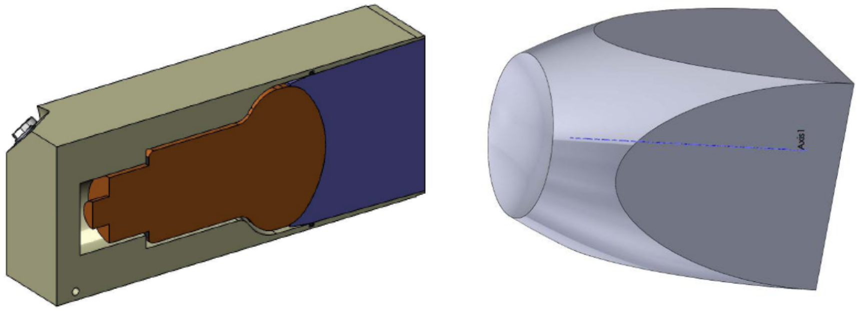
PROSPECT- Nx20



Multi-cell mechanical mockup

Internal reflectors

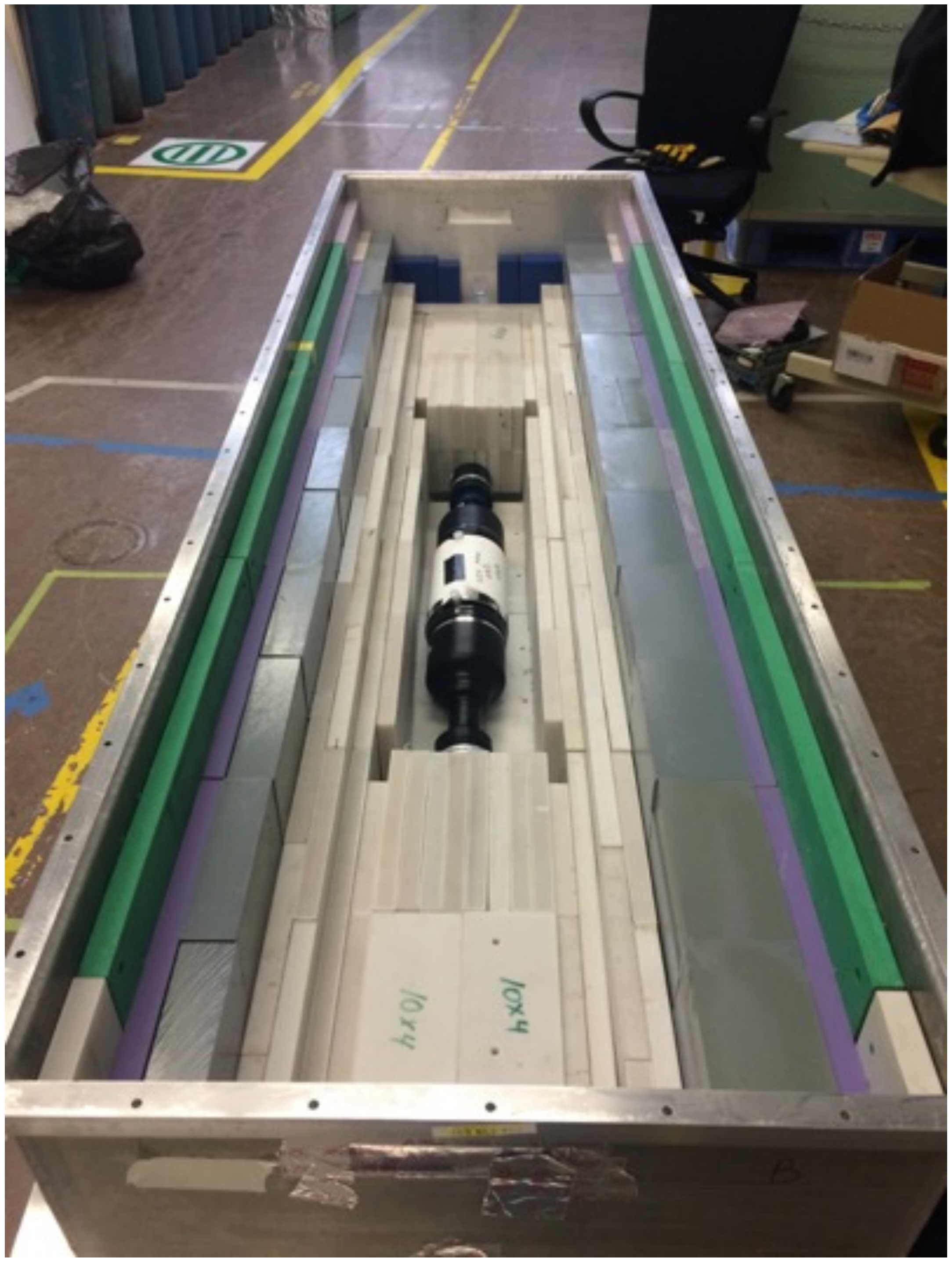




PMT Housing and Light Guides

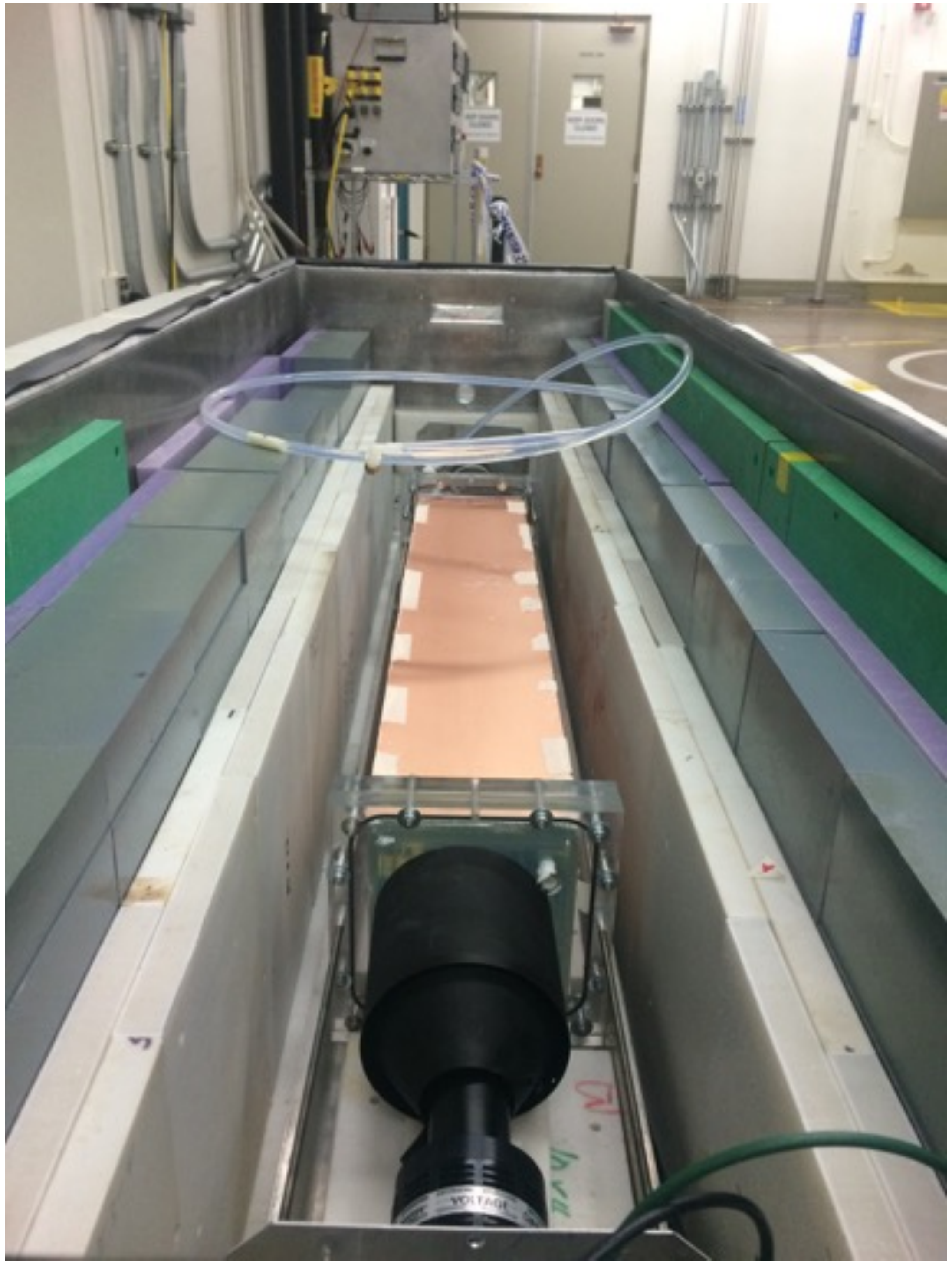
PROSPECT is actively continuing R&D to prepare for the building of Phase 1

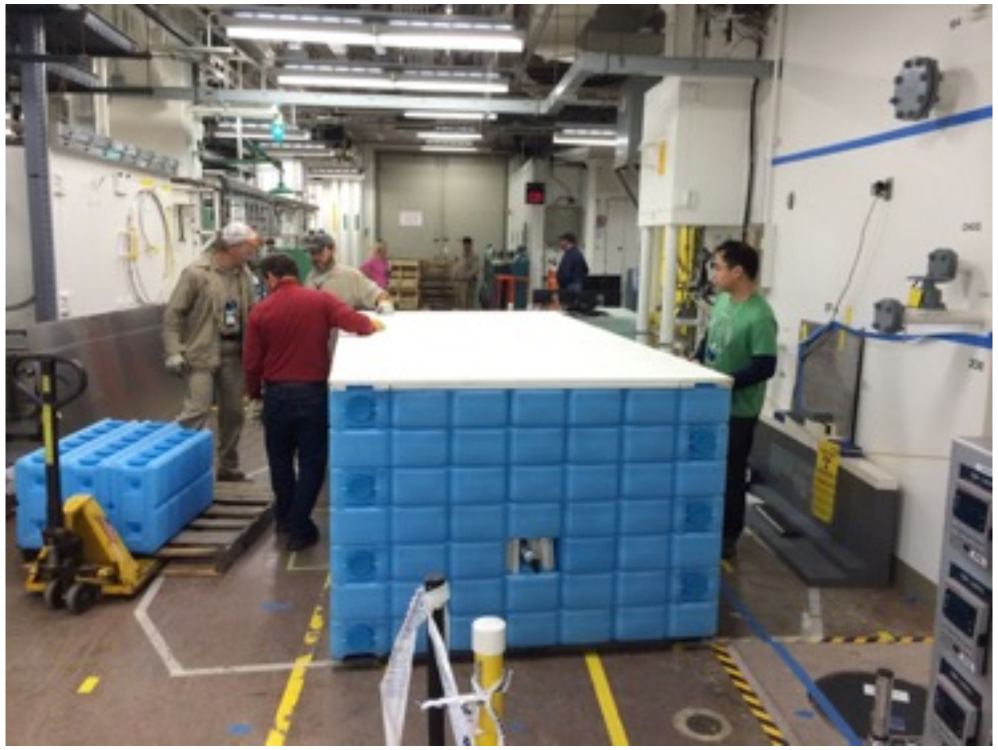
Back-up: PROSPECT-2 at HFIR



Detector geometry: 1.7L cylinder
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly
Reflectors: diffuse Gore
DAQ: CAEN 1720 (12bit)
Purpose: background reduction method

Back-up: PROSPECT-20 at HFIR



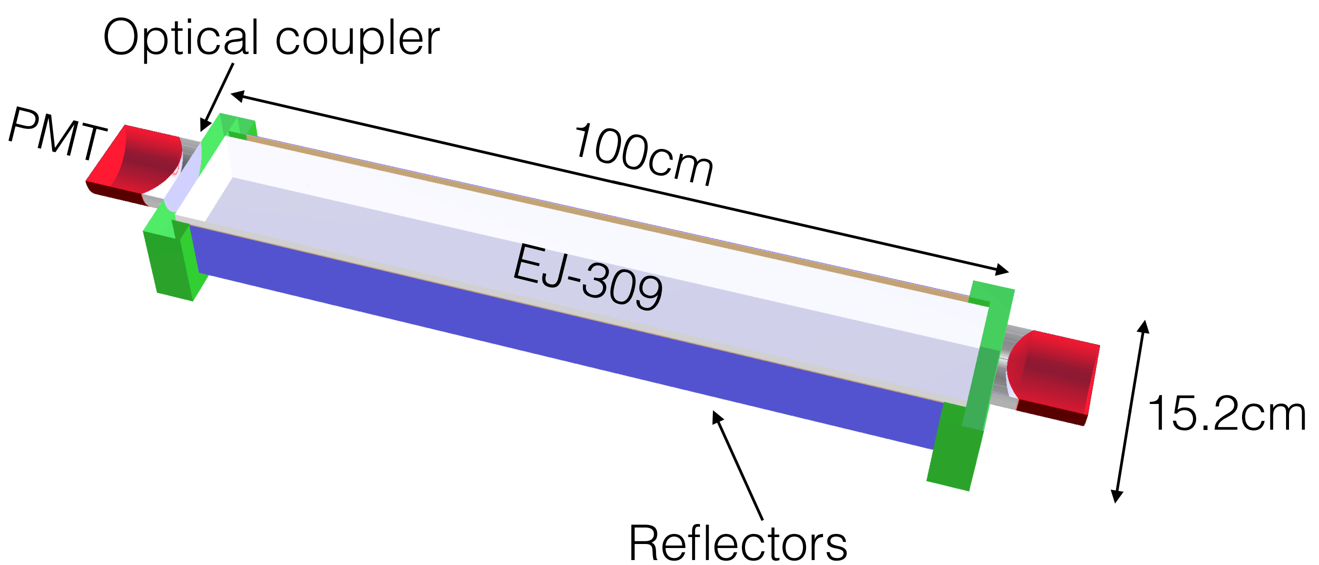


Detector geometry: 23L 1-meter rectangle
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly, water bricks
Reflectors: 3M SolarMirror
DAQ: CAEN 1720 (12bit)
Purpose: Operate full PROSPECT segment

Back-up: PROSPECT-20 at Yale

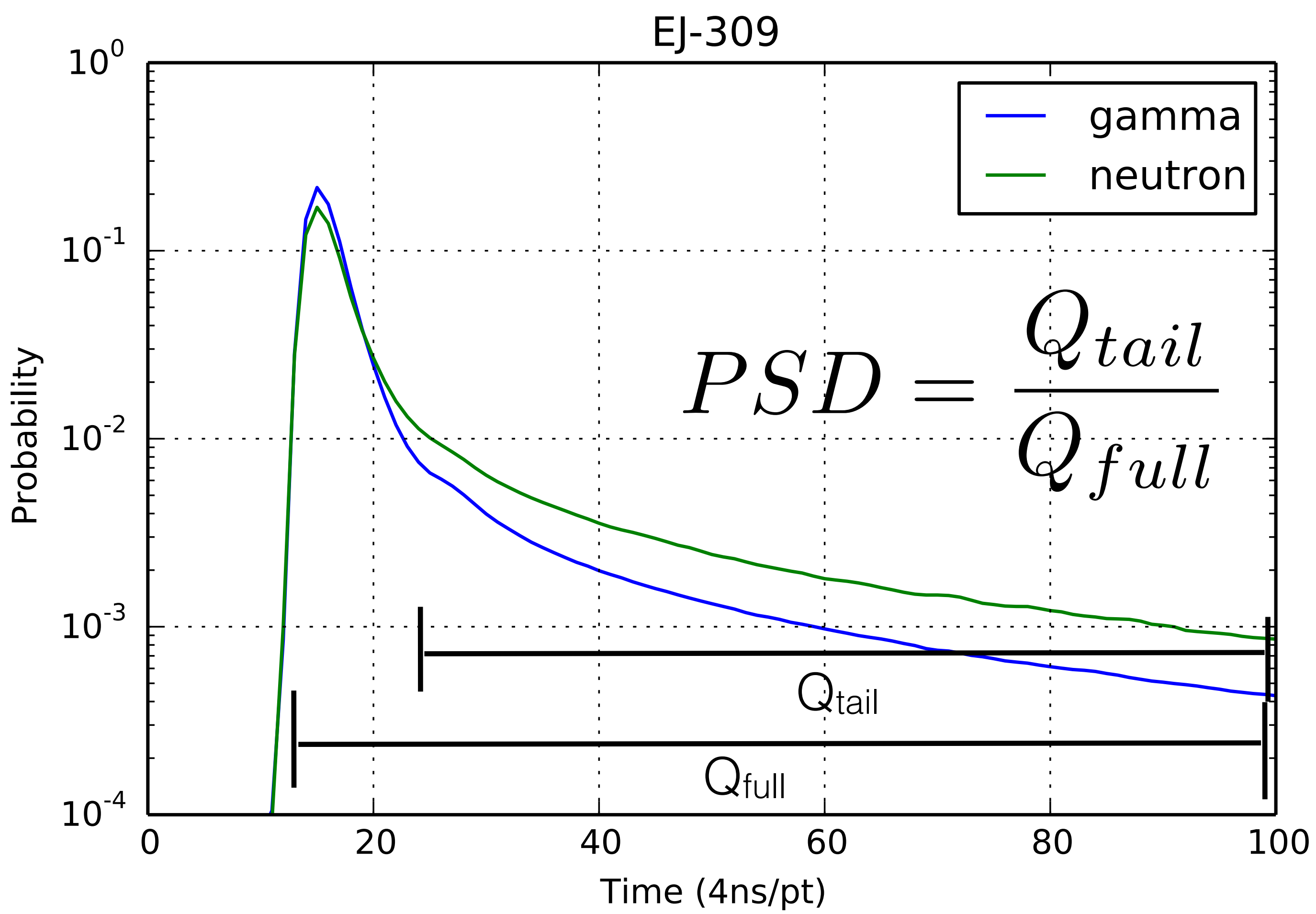
Optics optimization studies:
- Reflector type
- Reflector coupling
- PMT read-out
- Compare to simulation

Soon to come:
- Optical coupler geometries
- Li-loaded EJ-309



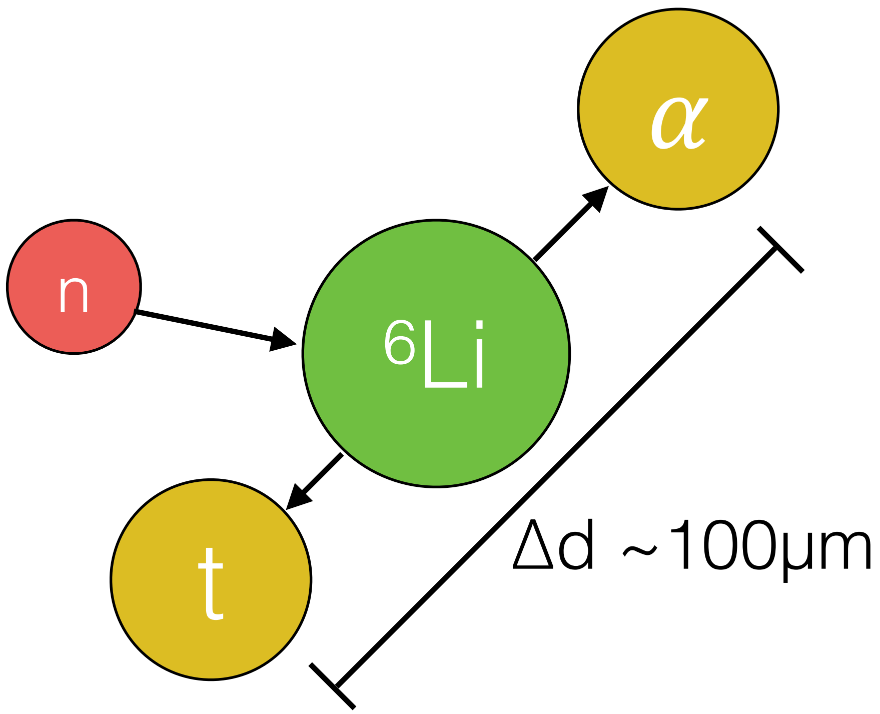
Detector geometry: 23L 1-meter rectangle
Scintillator: EJ-309
PMT(s): 5” spherical Hamamatsu R6594
Shielding: Pb
Reflectors: variable
DAQ: CAEN 1730 (14bit)
Purpose: optimize optics of full segment

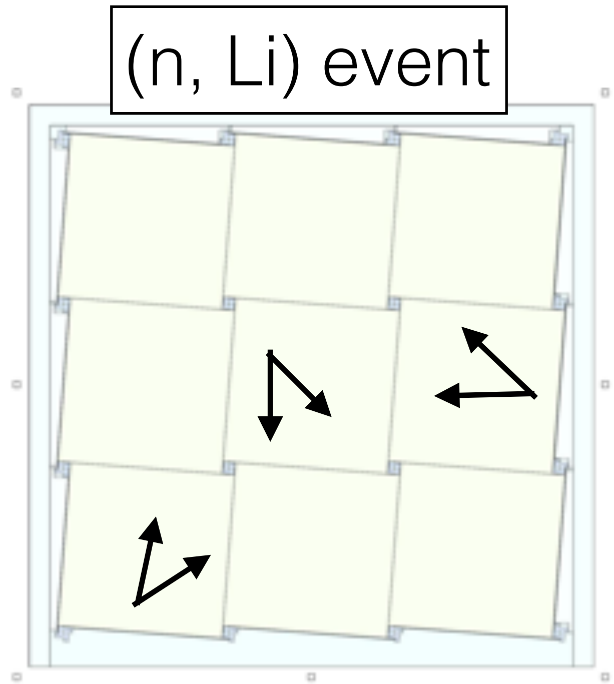
Back-up: PSD parameter



Lithium dopant in liquid scintillator

1. Small detectors that do not have full calorimetry information. But, neutron capture on ^{6}Li allows for single-site topology.

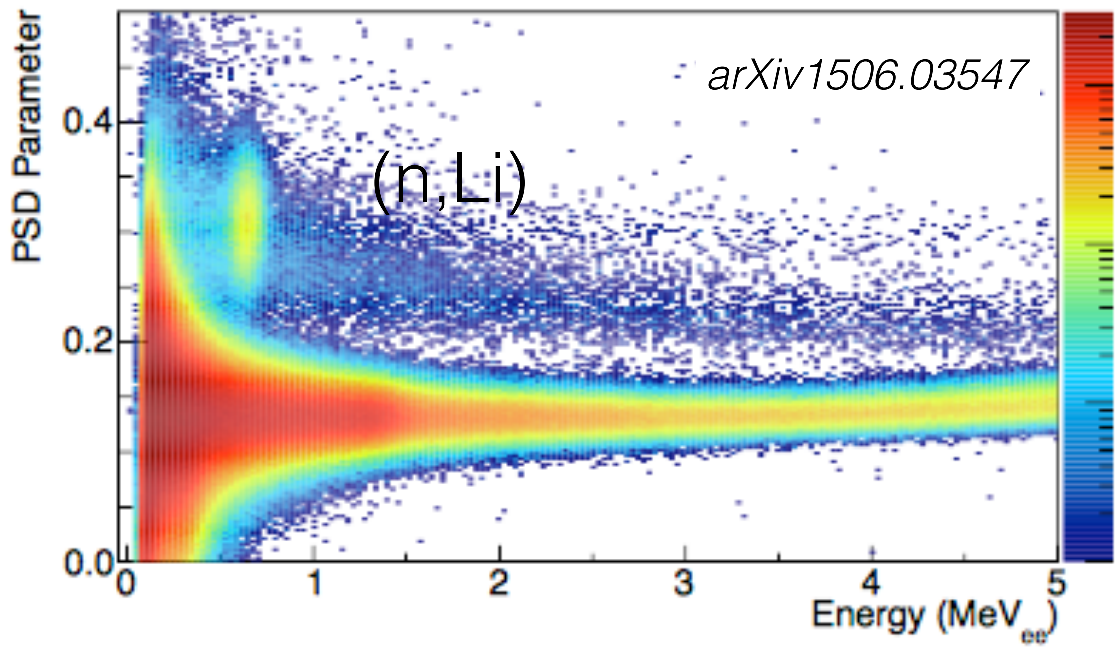


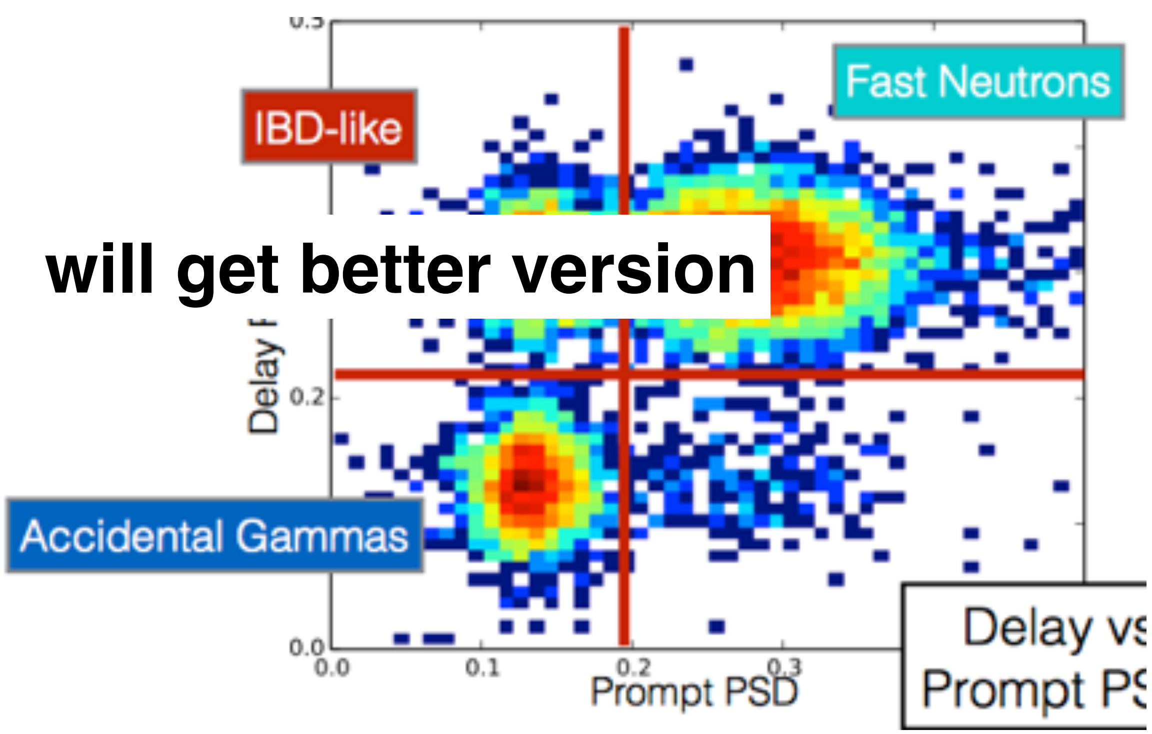


2. PROSPECT will be in a high gamma environment, with energies ranging from 1-10MeV. This background will not interfere with neutron captures since (n, Li) events fall in the "n-like" pulse shape discriminate (PSD) band.

Can contain (n, Li) events in segments and extract from backgrounds.

PROSPECT-2 at HFIR



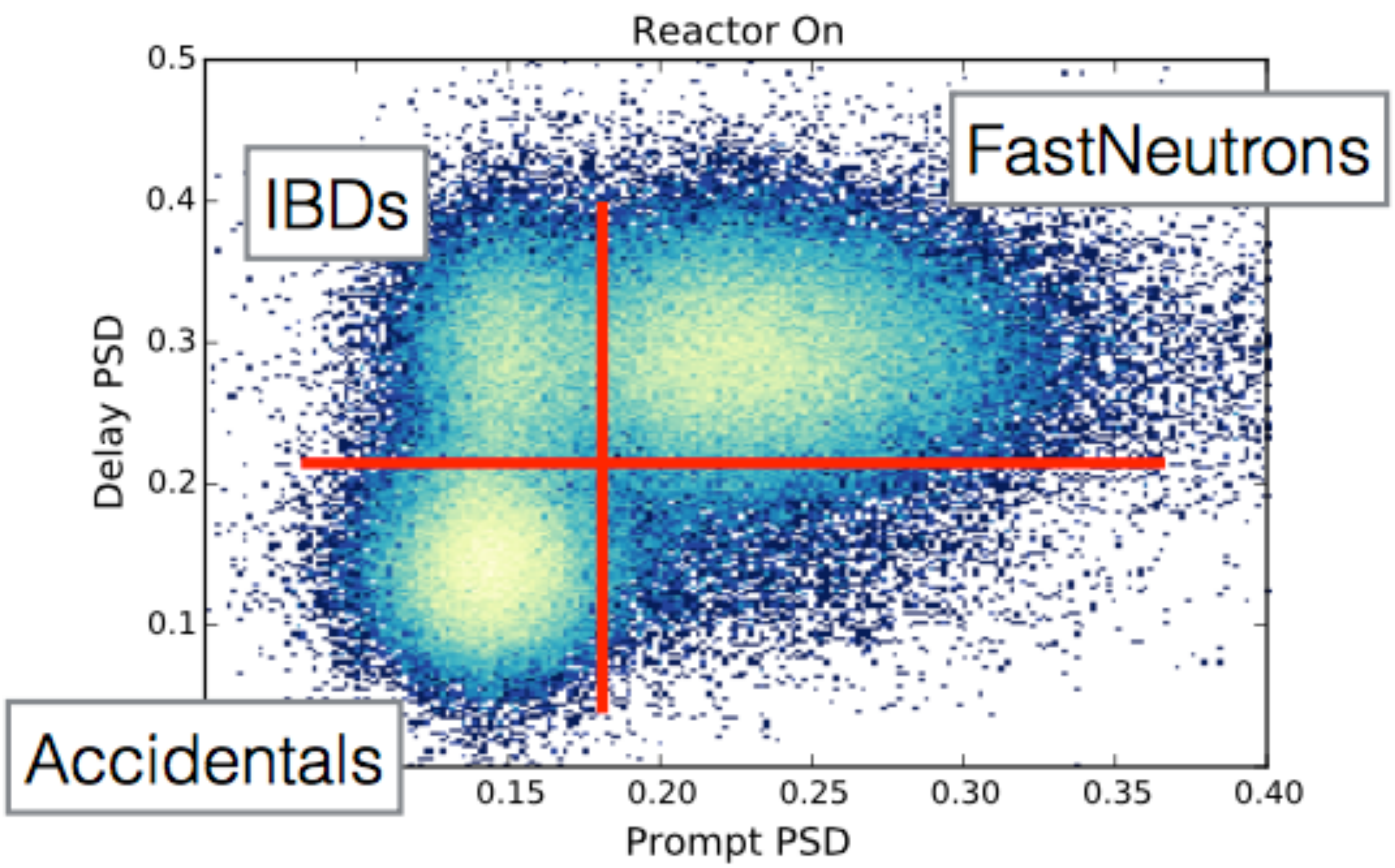


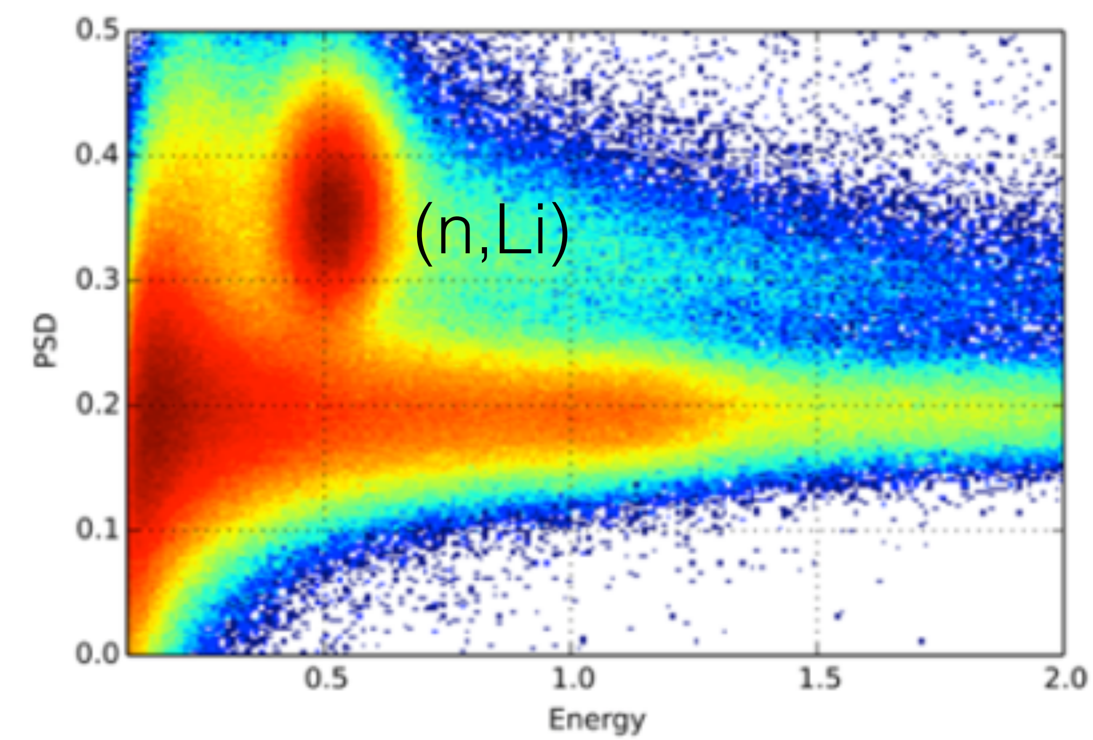
will get better version

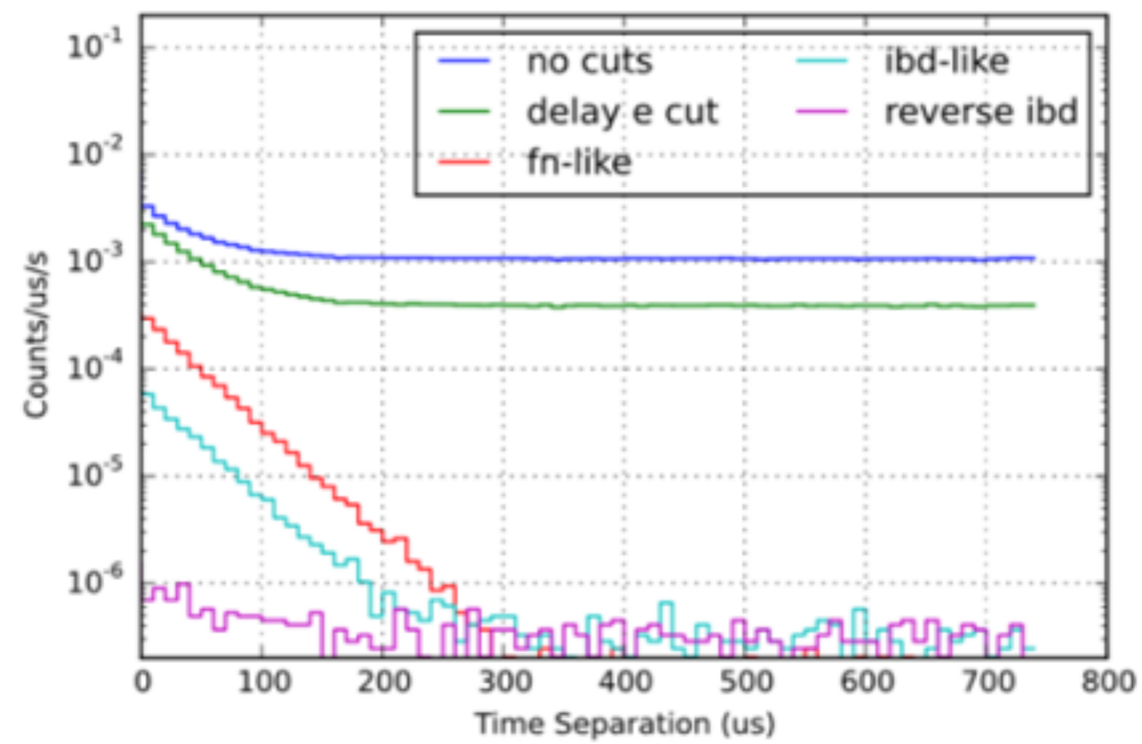
Coincidence analysis:
- cosmogenic fast neutrons (real)
- cosmogenic showers (multiple captures)
- reactor-related gammas (accidental)

PSD cuts on prompt and delayed signals rejects many of these backgrounds.

PROSPECT-20 at HFIR

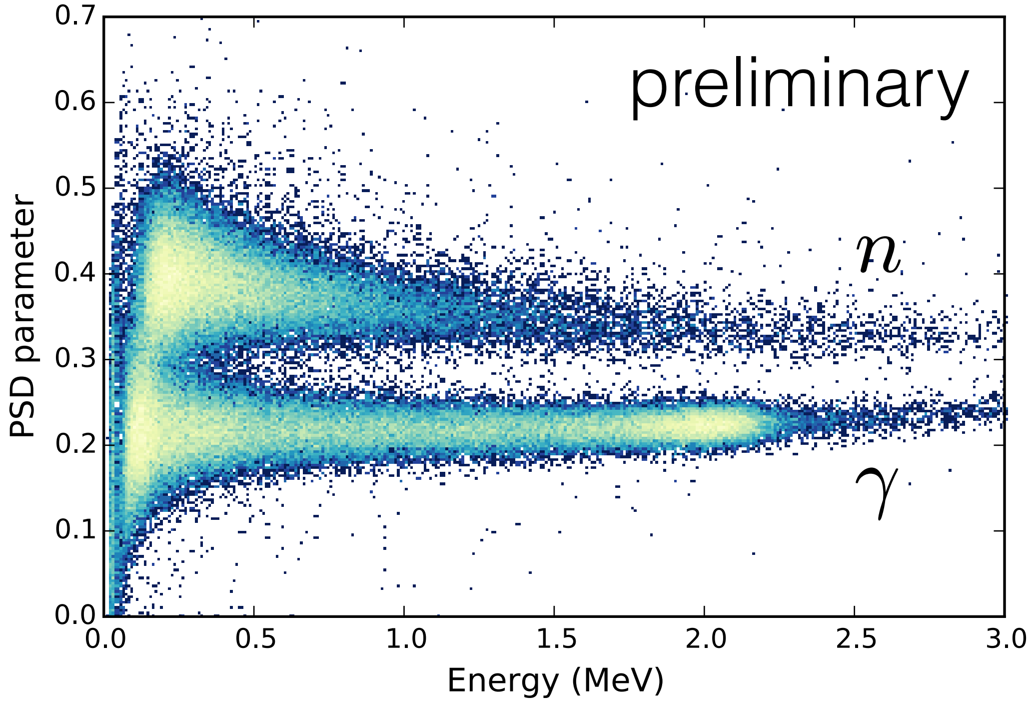


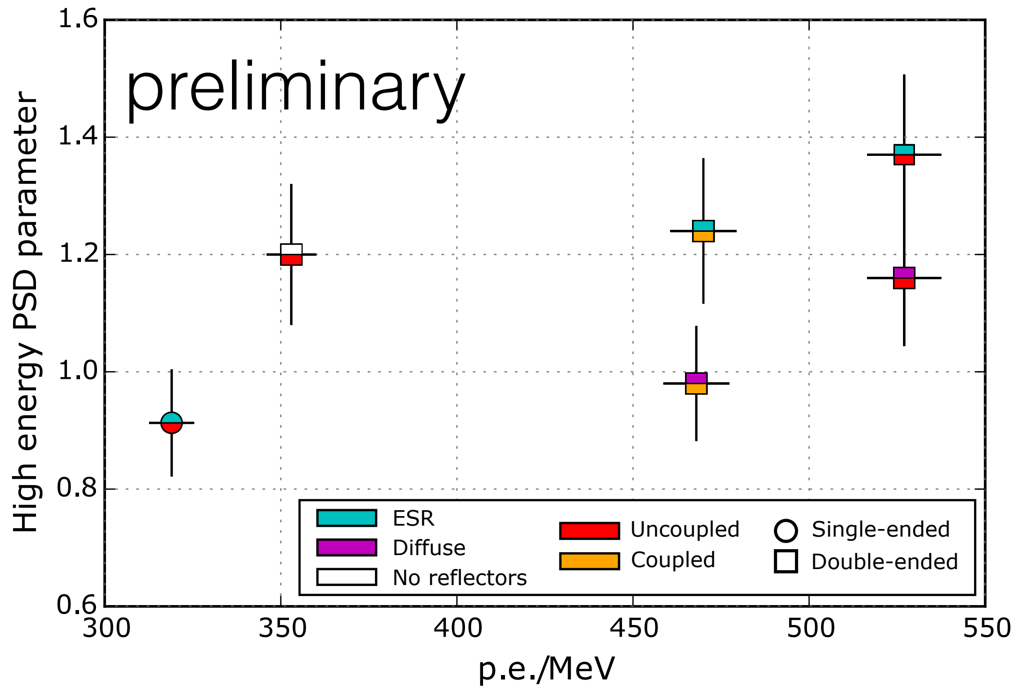




Accidentals reduced significantly with energy and PSD cuts.

PROSPECT-20 at Yale





- total internal reflection and specular reflectors give best collection and PSD
- double-ended PMT readout essential for uniformity