PROSPECT: A Precision Reactor Oscillation and Spectrum Experiment

N. Bowden, for the PROSPECT Collaboration

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Lawrence Livermore National Laboratory

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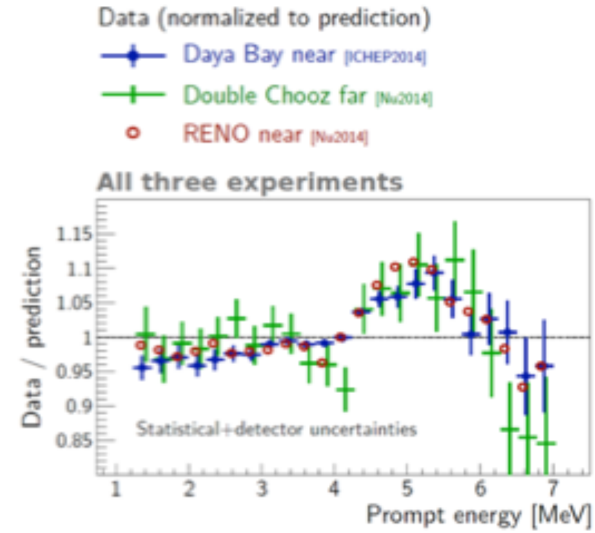
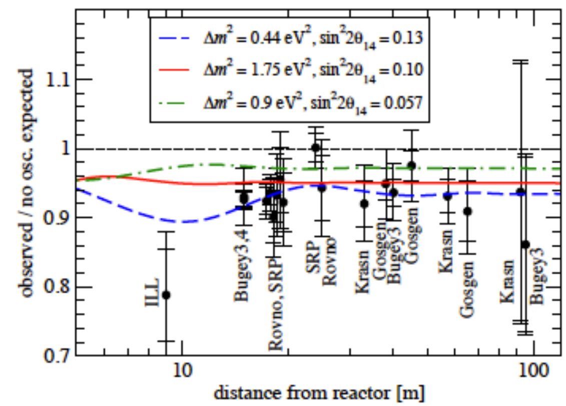
Scientific and Applied Motivations

- **Precision measurement of ^{235}U reactor antineutrino spectrum**
  - additional constraint on models seeking to explain newly observed spectral feature
  - benchmark measurement for monitoring efforts

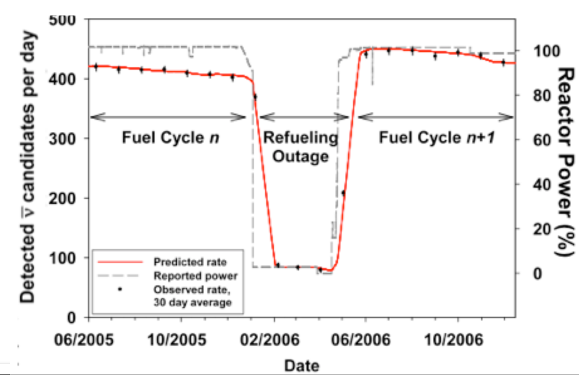
  See: B. Littlejohn, Tues. afternoon



- **Short Baseline Oscillation search:**
  - directly address sterile neutrino explanation of electron neutrino disappearance anomalies

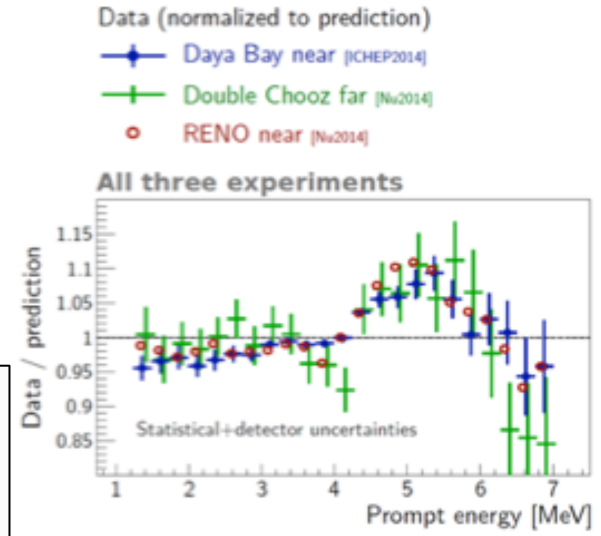


- **Reactor Safeguards:**
  - develop detection technology for operation near-surface and proximate to research reactor

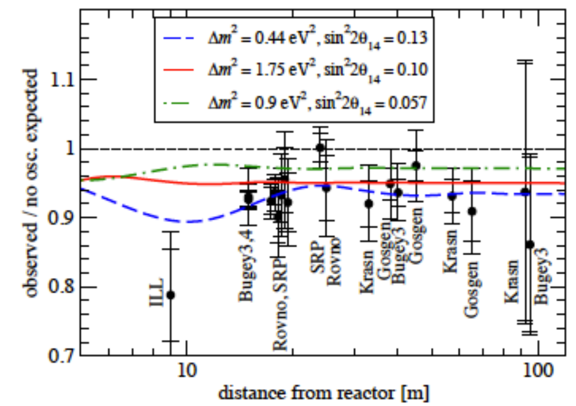


Requirements

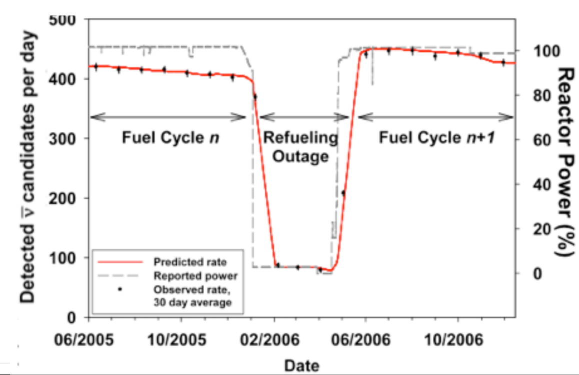
- **Precision measurement of ^{235}U reactor antineutrino spectrum**
  - high light yield; well characterized & uniform response
  - low inactive mass
  - good e^{+} event containment



- **Short Baseline Oscillation search:**
  - spectral measurements over wide baseline range
  - compact core reactor and access to short baseline deployment location(s)



- **Reactor Safeguards (and all of the above):**
  - rejection of cosmogenic correlated backgrounds for aboveground operation

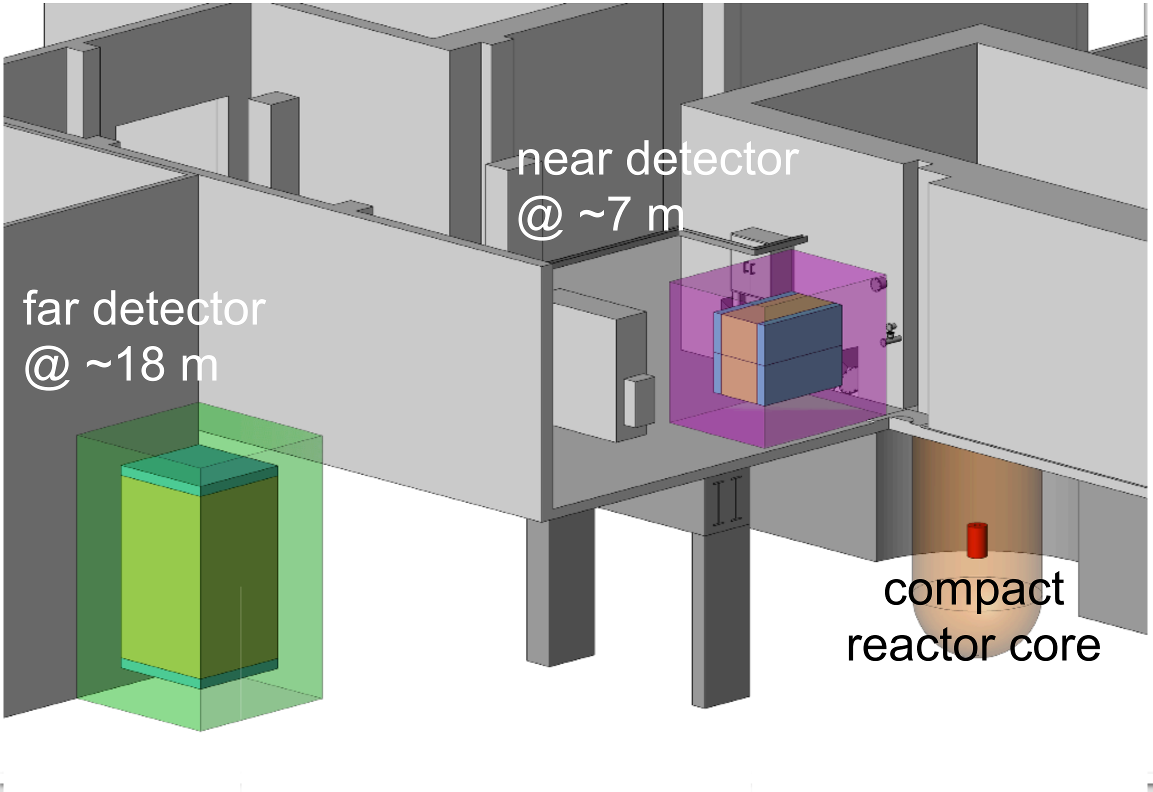


PROSPECT Conceptual Design

Deploy two segmented liquid scintillator detectors close to compact research reactor core:

Phase 1: Near detector *O*(2ton) - Precision spectrum measurement and oscillation search

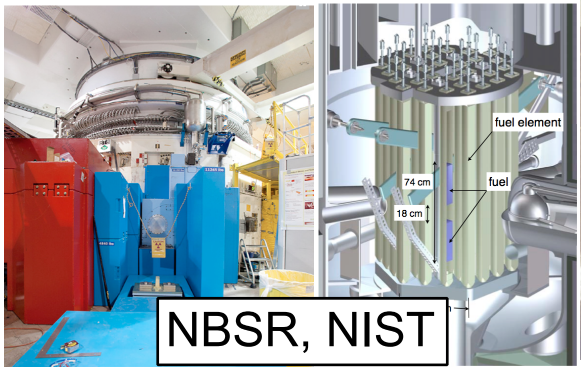
Phase 2: Near + Far detector *O*(10ton) - Enhanced oscillation search

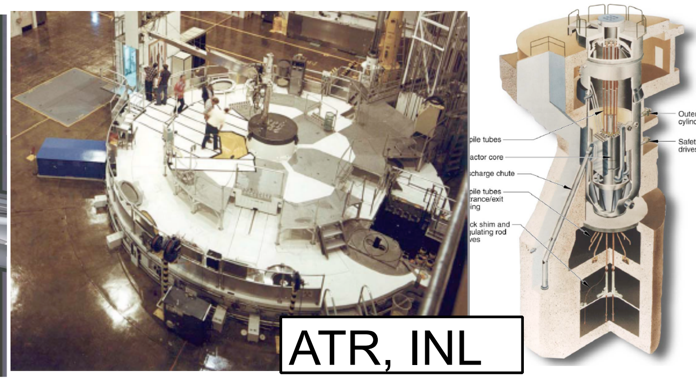


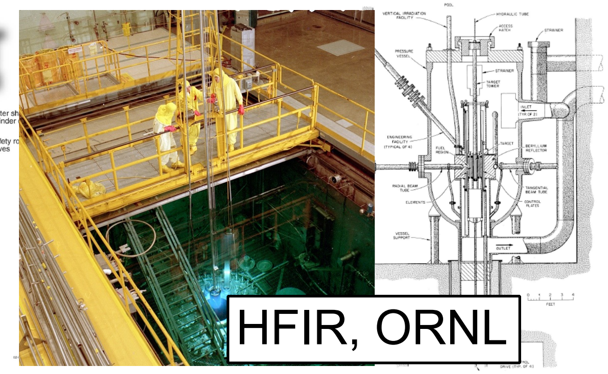
Unique Features

- ^{6}Li doped liquid scintillator
- excellent energy resolution
- low dead volume
- movable near detector

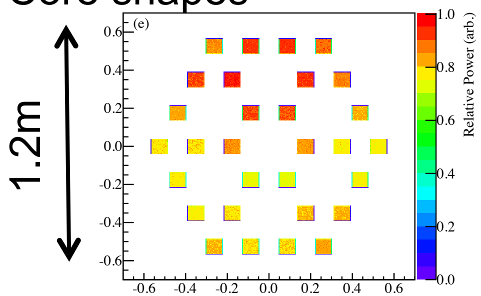
U.S. High Power Research Reactor Facilities

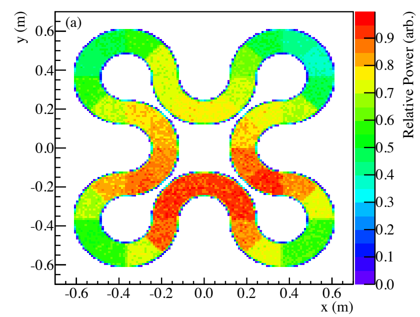


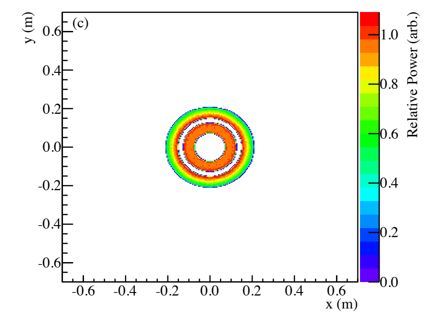




Core shapes







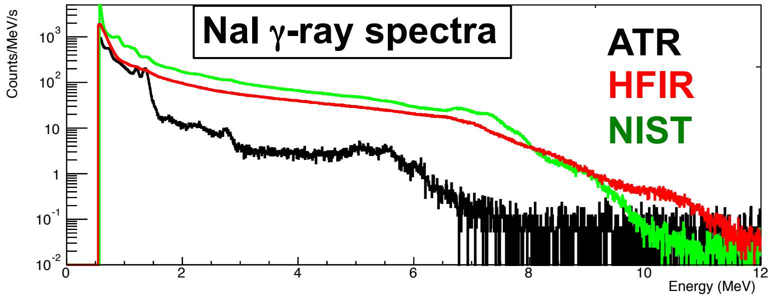
Advantages

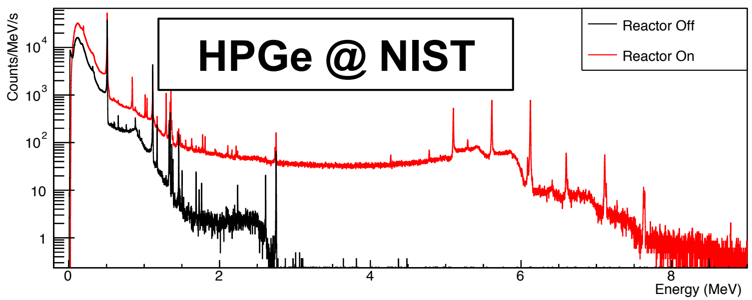
- Compact HEU core
- Frequent outages for background measurement
- Multiple accessible baselines
- Detailed core models

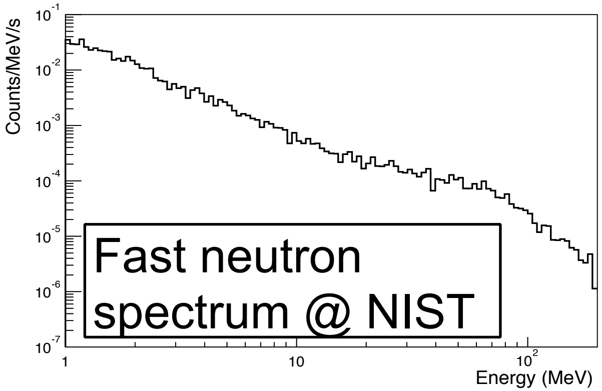
Site	Power	Duty Cycle	Near Baseline	Average Near Flux	Far Baseline	Average Far Flux
NIST	20 MW_{th}	68%	5.3m	1	17.0m	1
HFIR	85 MW_{th}	41%	7.9m	1.1	17.9m	2.3
ATR	110 MW_{th}	68%	10.1m	1.5	18.8m	4.5

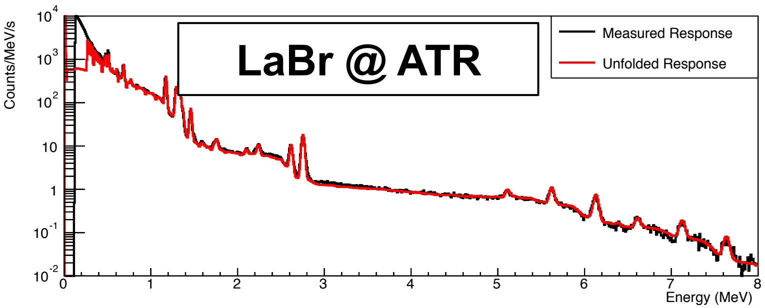
Background Measurements

- Extensive work at all sites:
  - γ-ray spectra & spatial surveys
  - fast/thermal neutron flux
  - muon flux









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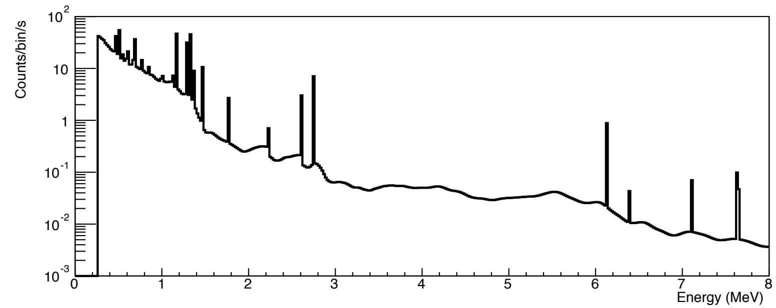
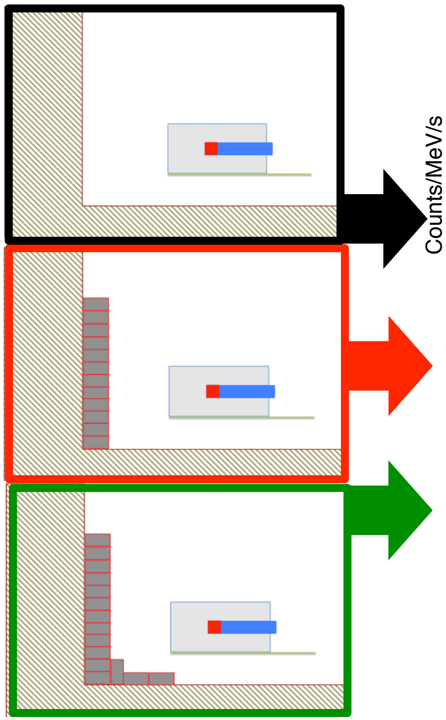


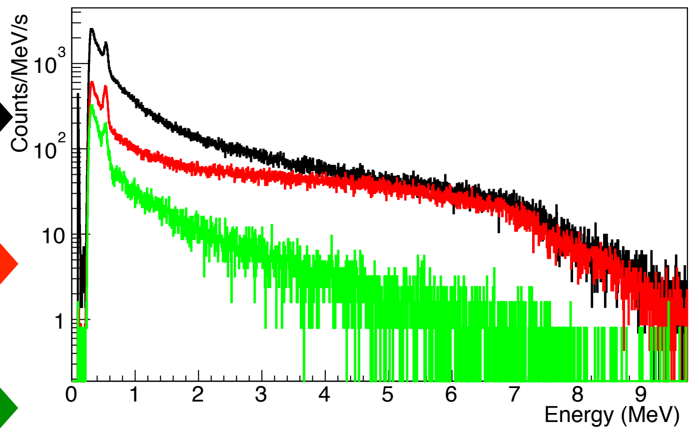
Background Paper in preparation

Background Measurements

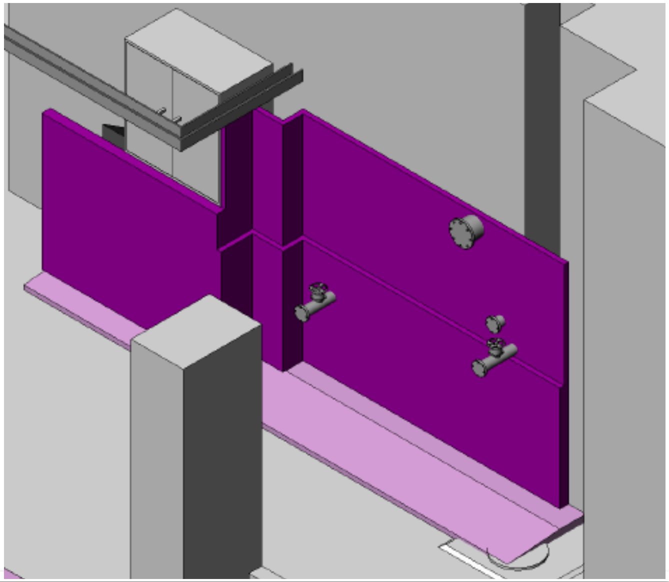
- Important findings:
  - significant spatial & temporal variations due to nearby activities & systems
  - high energy γ–rays primarily due to local neutron interactions on water and iron
  - cosmogenic rates vary with elevation and overburden as expected

Detailed background characterization and targeted shielding design are essential



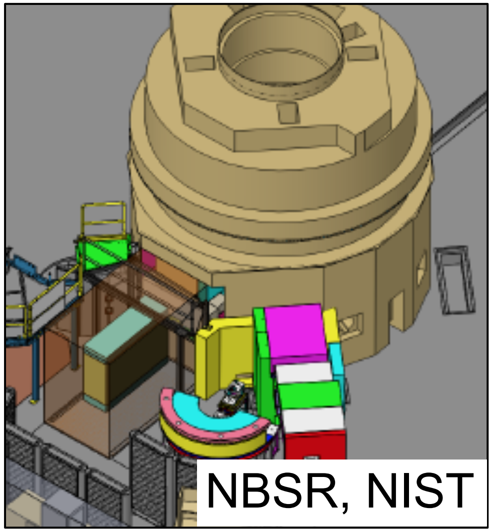


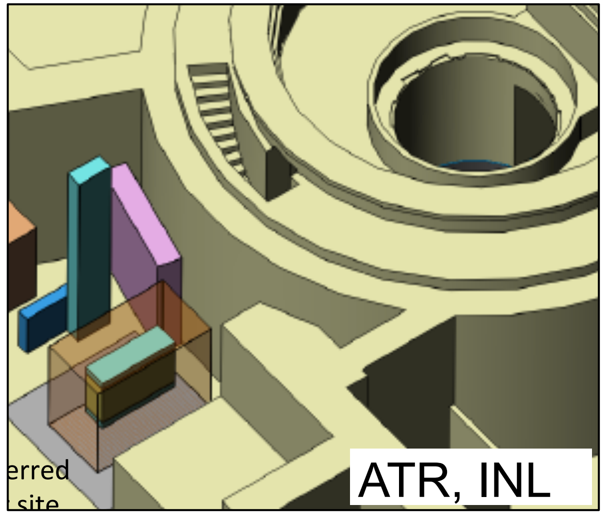
Detailed interpretation underway; understanding sufficient for local shielding design

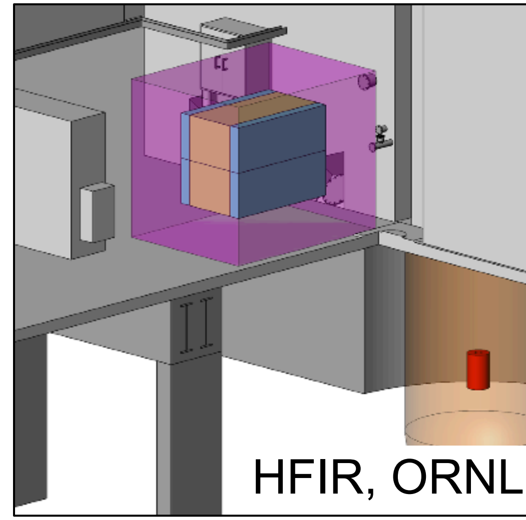


Background Paper in preparation

Site Engineering and Logistics







- Enthusiastic engagement from management and staff of all sites
- Examined detector locations in detail:
  - Floor loading, space and access constraints, certification, physics potential, …
- PROSPECT is viable at all sites

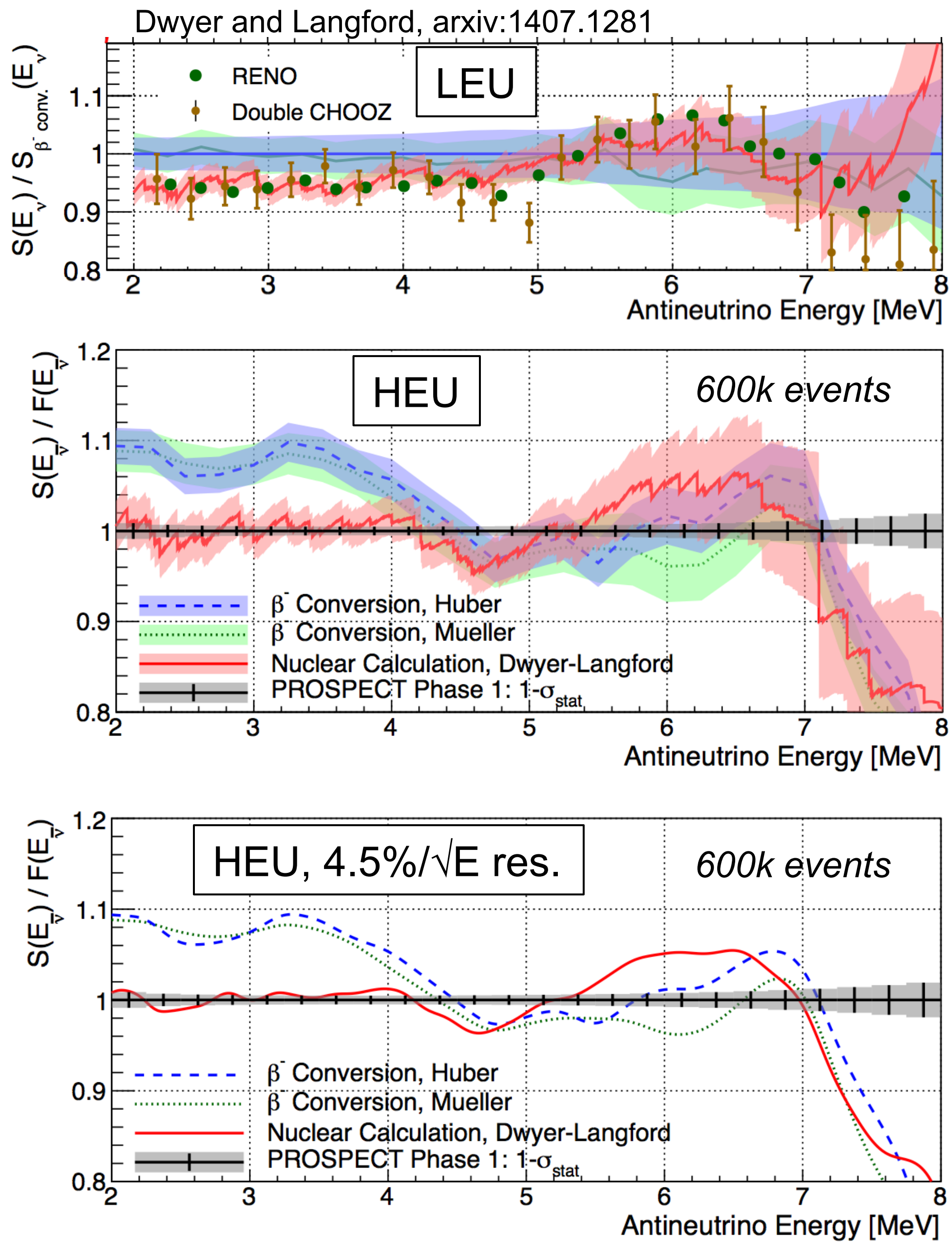
HFIR selected as preferred site for Phase 1

Physics Potential: Spectrum Measurement

- Single component HEU core measurement will complement existing LEU spectrum measurements
  - Additional model constraint from single, well modeled, reactor

- With goal resolution of 4-5%, sensitive to fine structure:
  - Potential constraints on yields, endpoints of various branches (reactor spectroscopy)?
  - Provide input for future high-resolution reactor experiments (JUNO)?

- Clearly, must ensure excellent control of energy scale and efficiency systematics

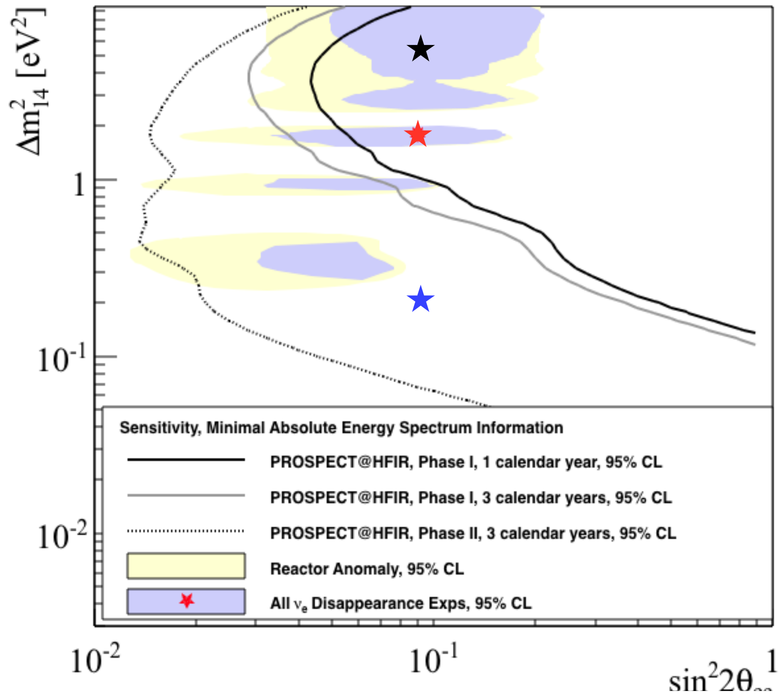


Physics Potential: Oscillation

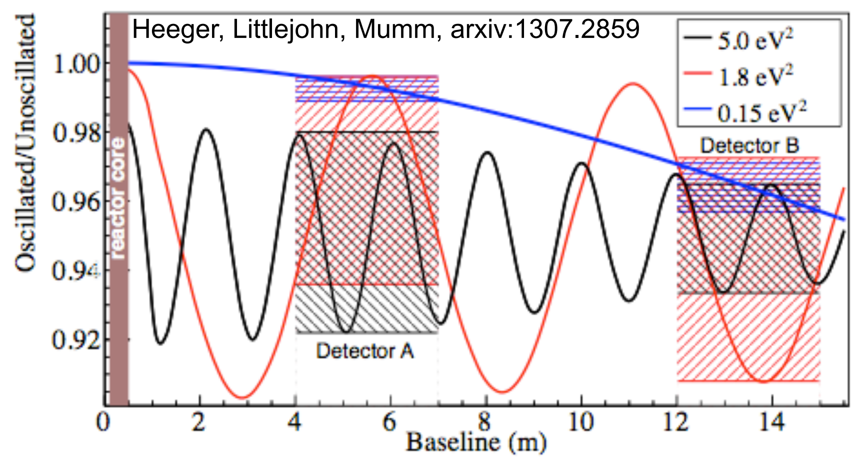
Multiple segmented detectors probe wide L/E span, improving sensitivity over Δm^2 range of interest.

Phase I can rapidly provide significant physics potential

Phase II can address majority of suggested phase space

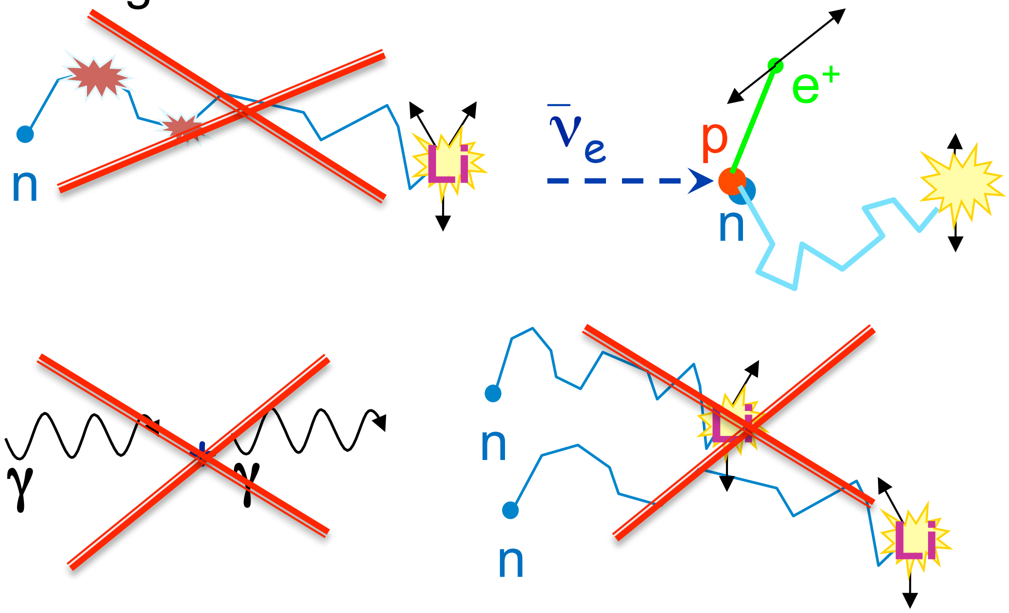


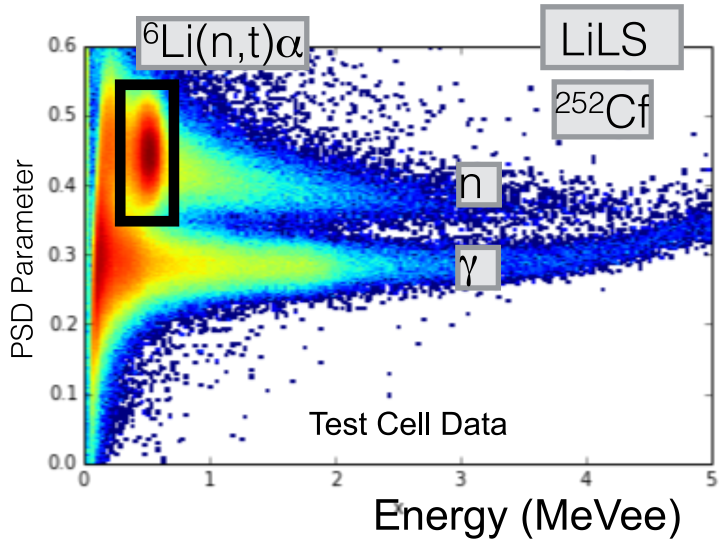
- Assumptions:
  - 1:1 Signal:Background
  - Detection Efficiency: 30%
  - 14.6cm position resolution
  - 10% energy resolution
  - No reliance on absolute spectral shape or normalization: pure relative measurement

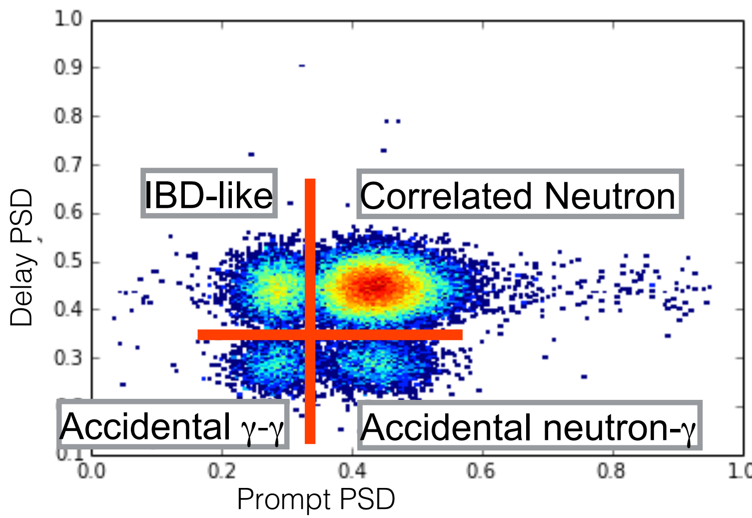


Background Rejection & Signal Selection

- ^{6}Li-capture, Pulse Shape Discrimination, and topology from segmentation
- Strong rejection of accidental and correlated backgrounds







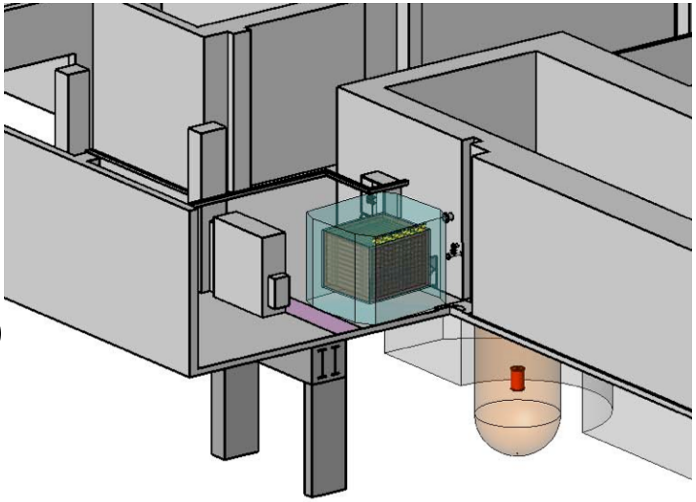
- Using simulation/deployment data to understand and mitigate electromagnetic-neutron capture correlated backgrounds

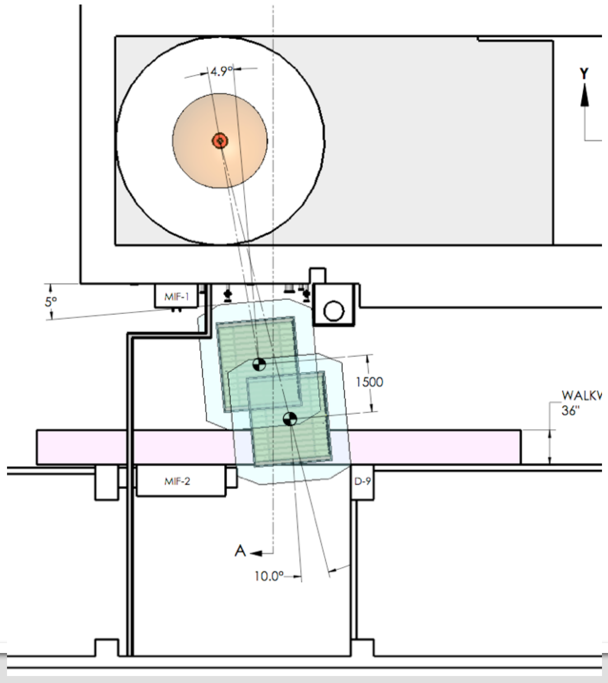
PROSPECT Phase I Detector Concept

2.5 ton active target at < 8 m baseline
(140 segments, 280 channels)

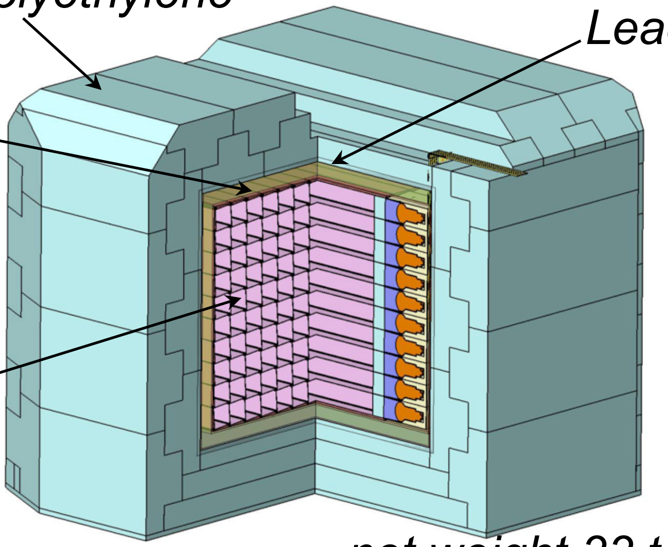
Single liquid tank containing full cell assemblies

Movable (airpads) to cover larger baseline (+1.5 m)
- Extends sensitivity to lower Δm_{14}^2
- Provides systematic checks



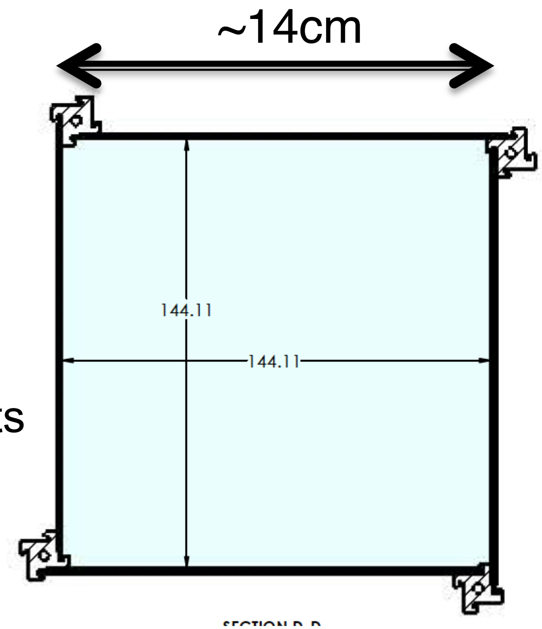


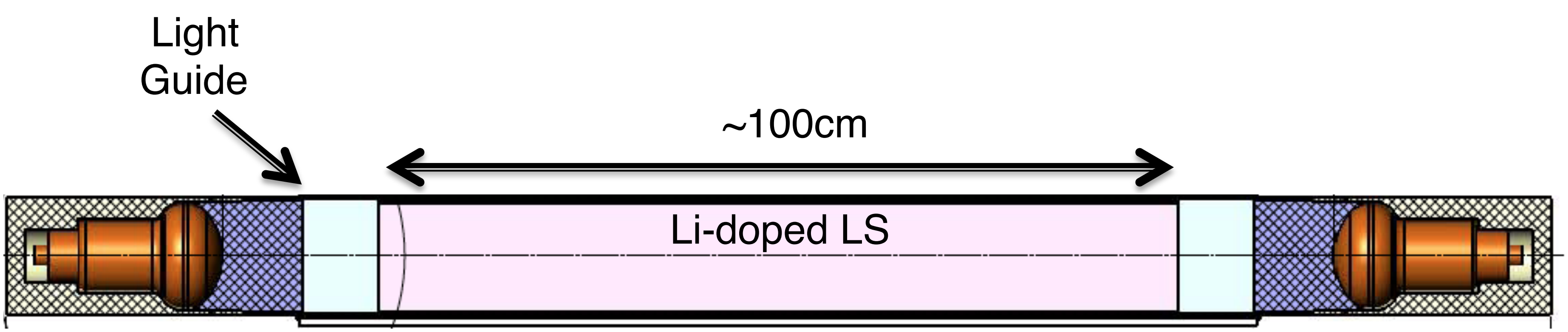
Veto system under consideration



Detector Development– Segmentation Concept

- 2D segmentation provides 3D position resolution, reasonable channel count, and space efficiency
- Need for minimal dead material guides design
  - Goal: < 2% dead material (>15% for Bugey3)
- "Unit cell" built from reflecting separators and longitudinal posts – allows excellent calibration access
- Sealed PMT modules couple via acrylic light guides



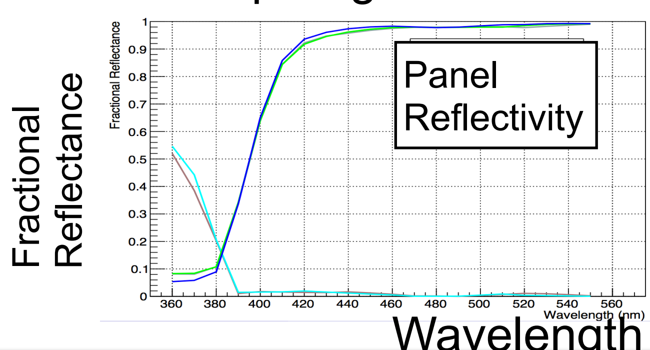


Detector Development – Separators and LS

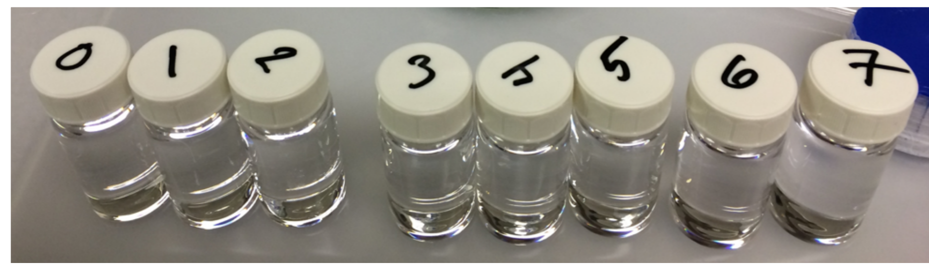
- Reflecting segment system
  - Fabrication method identified
  - Testing multiple material options

Short Mockup Segment

Specular Panel

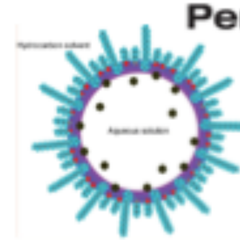


- Li-loaded Scintillator:
  - Formulation methods identified
  - Several candidates with good scintillation light yield, capture timing, PSD, compatibility



PSD enhanced LAB-LS doped with BNL ^{6}Li chemistry

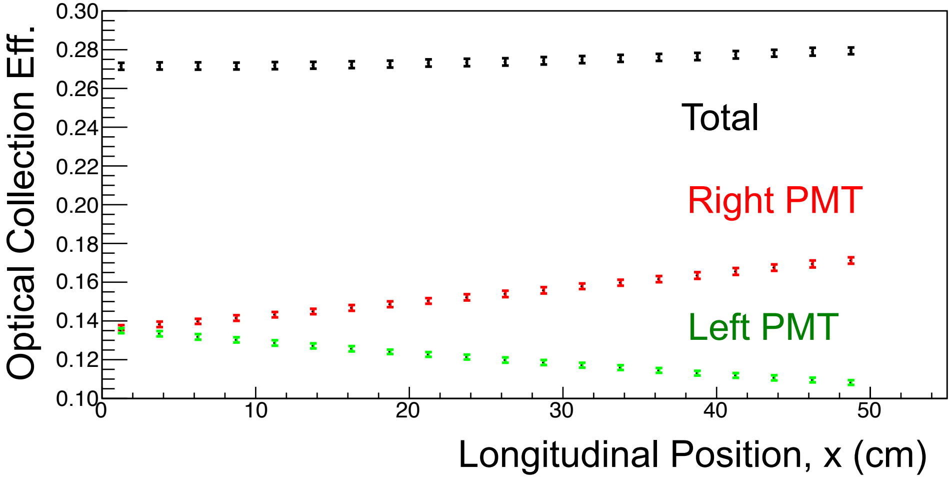
PerkinElmer



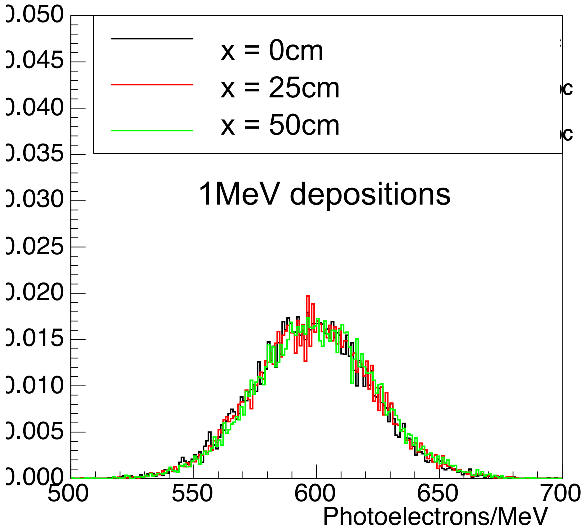
Ultima-Gold doped with NIST ^{6}Li micro-emulsion

Detector Development – Response Studies

- Geant4 simulation tools used to study detector response – a few examples:

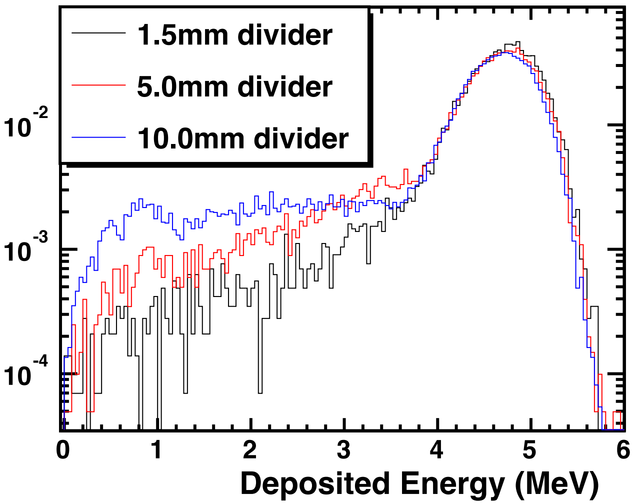


Total optical collection efficiency is inherently quite uniform – a simple amplitude ratio correction provides uniform response and reasonable position estimator



Simple position correction maintains uniform energy response along segment.

Resolution ~ 4%//√E using realistic optical parameters



Variation of e+ response with separator thickness (conservative 10%/√E smearing applied)

PROSPECT progression

Measure n, γ bkgs

Run DAQ,
Remote data-taking

Examine n-Li PSD, validate background simulation

Demonstrate shielded background rates

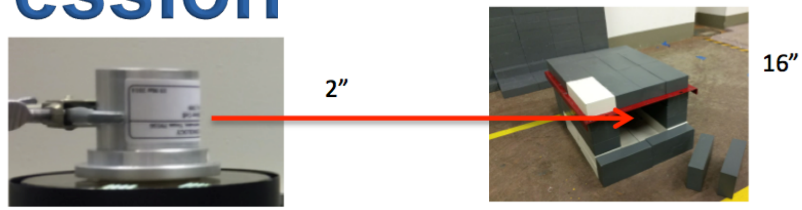
Demonstrate full-cell PSD, light yield

Deploy final design concepts

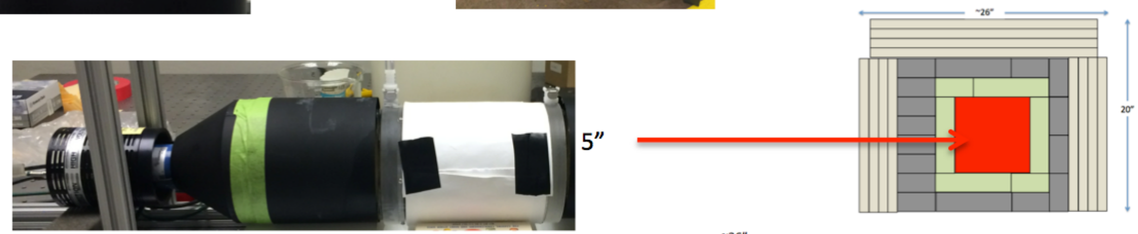
Study relative segment responses

Aim for antineutrino detection

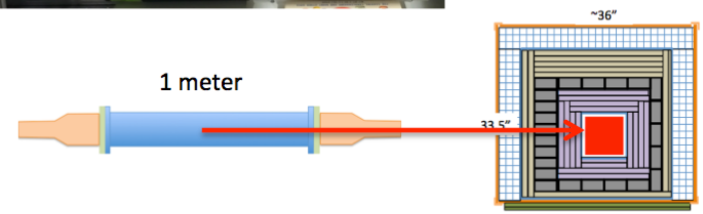
PROSPECT 0.1
Aug. 2014 *



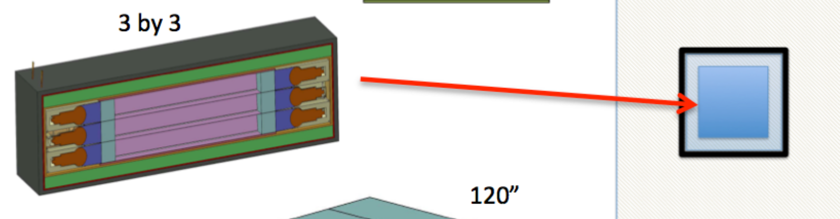
PROSPECT 2
Dec. 2014 *



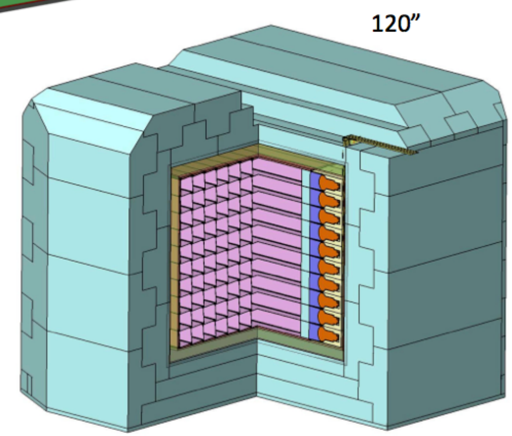
PROSPECT 20
Jan. 2015 *



PROSPECT 200



PROSPECT 2ton



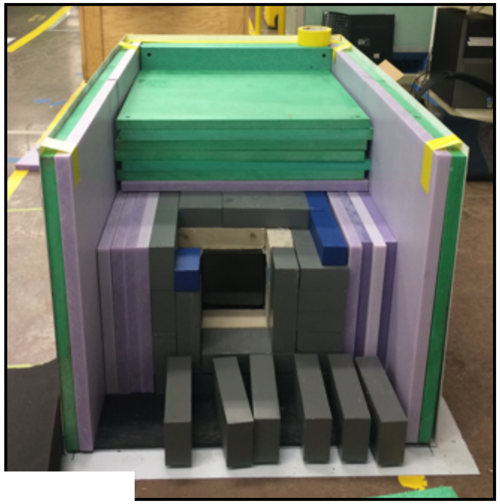
* Deployment complete/imminent

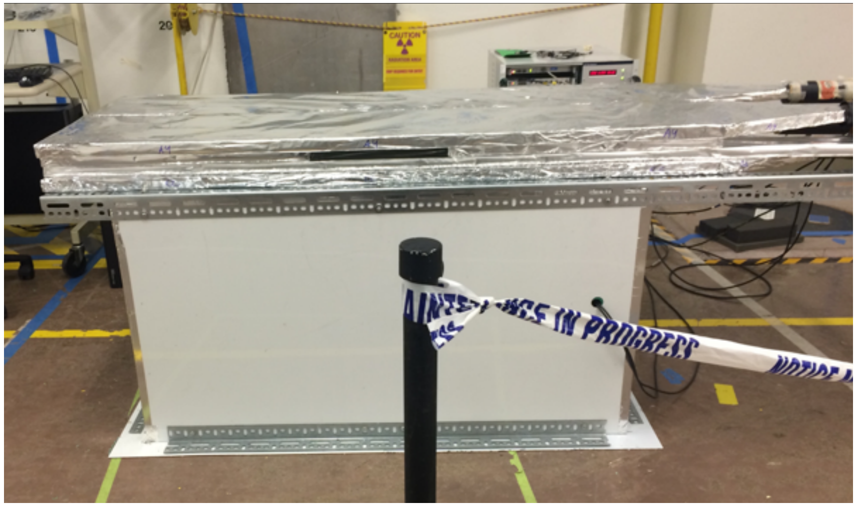
Approximate mass kg

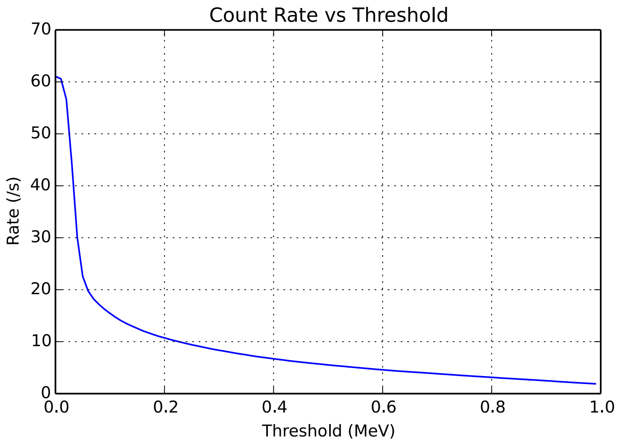
Hot off the press: PROSPECT2 operating @ HFIR

~2 liter Li-LS detector in small B-poly/ lead shield

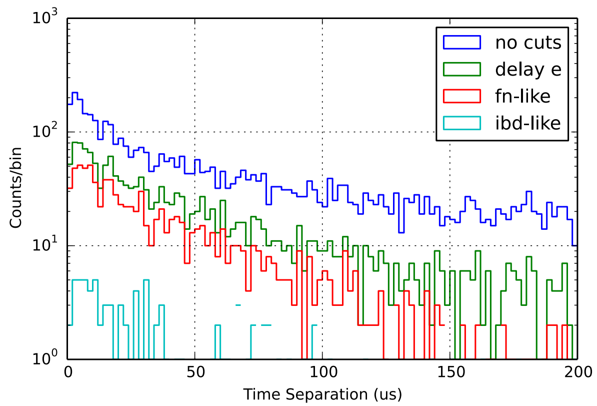
- not representative of final shield design but useful for MC validation







10Hz Rx On singles rate > 200keV
-several orders of magnitude reduction with more to come



^{6}Li and fast neutron PSD strongly suppress backgrounds

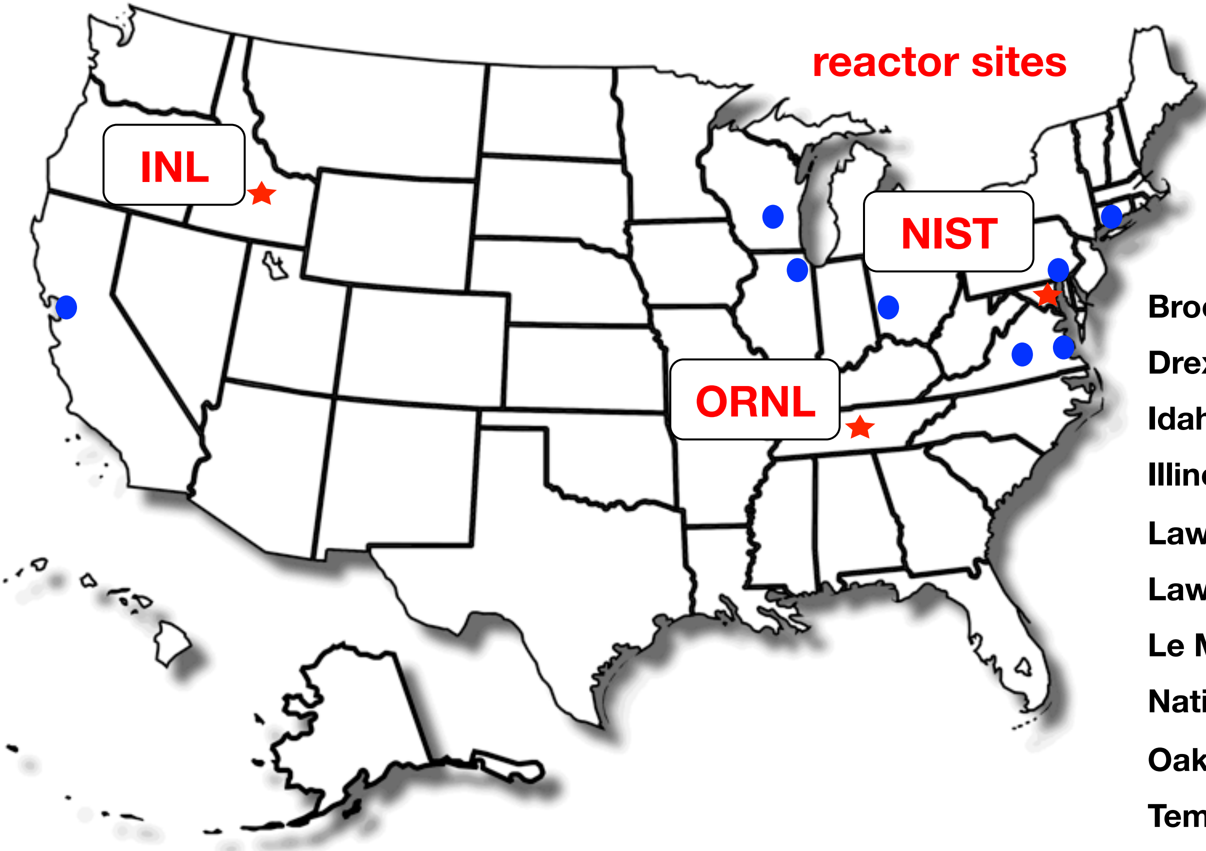
Studies Underway:

- Muon correlations
- Detailed simulation comparison
- Internal background contribution (Rx off)
- …

Conclusions

- Much has been learned about the absolute reactor antineutrino flux and spectrum in recent years
- More experimental data is needed to address persistent questions
- PROSPECT can provide timely input by measuring ^{235}U reactor antineutrinos at short baselines
  - High energy resolution allows a precise absolute spectral measurement for providing new constraints on reactor models
  - Good position resolution allows relative spectral measurements at different distances for testing the oscillation interpretation of the reactor anomaly
- Detector R&D, site characterization, and prototype deployments are well underway
- PROSPECT detector development and measurements are directly applicable to monitoring applications

PROSPECT Collaboration



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Yale University

10 universities
6 national laboratories