Updates from the PROSPECT Reactor Antineutrino Experiment

September 20, 2023

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On Behalf of the PROSPECT Collaboration

PROSPECT Physics Motivations

- Probe short-baseline neutrino oscillations

  PROSPECT, PRL 121 (2018) PROSPECT, PRD 103 (2021) TBD (2023) TBD (2024)

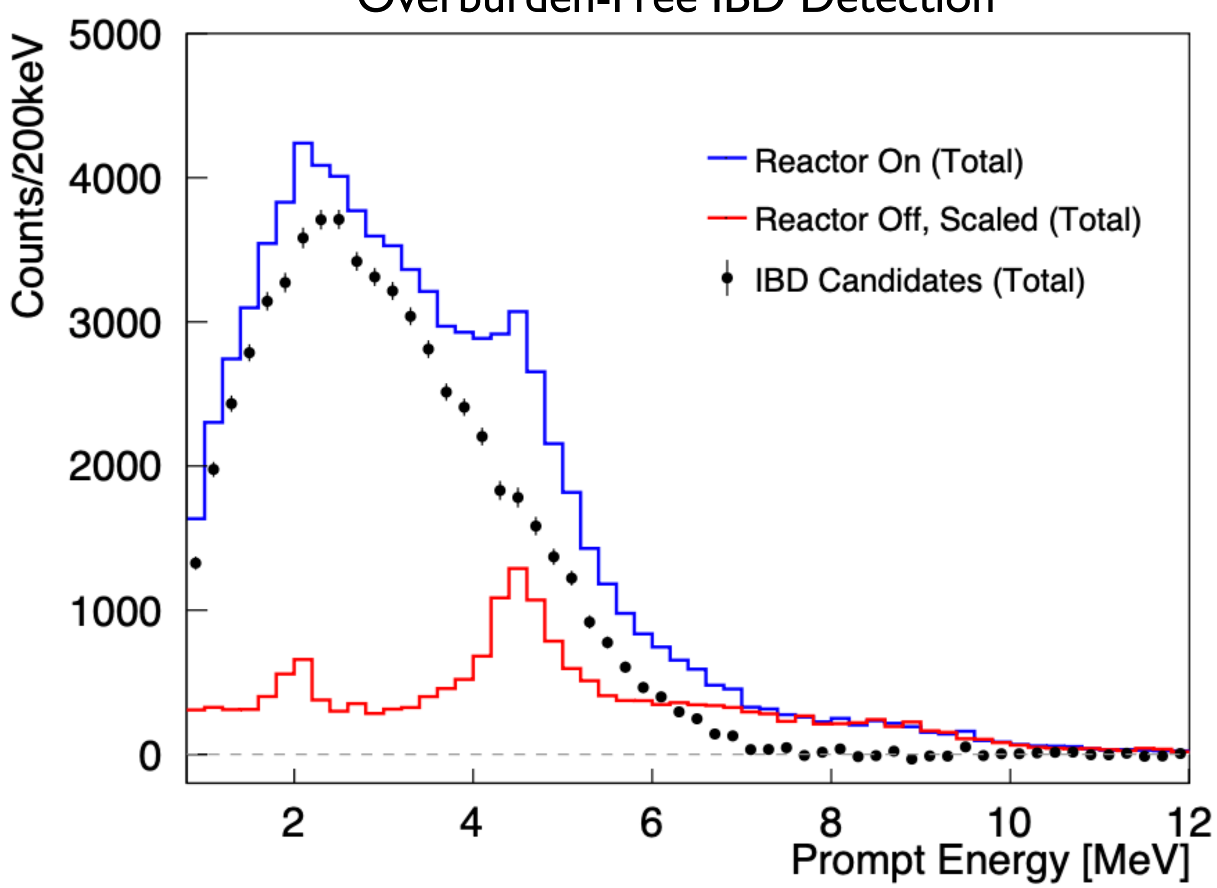
- Measure reference antineutrino spectrum and flux for ^{235}U

  PRL 122 (2019) PRD 103 (2021) PRL 128 (2022) PRL 128 (2022) PRL 131 (2023) TBD (2024)

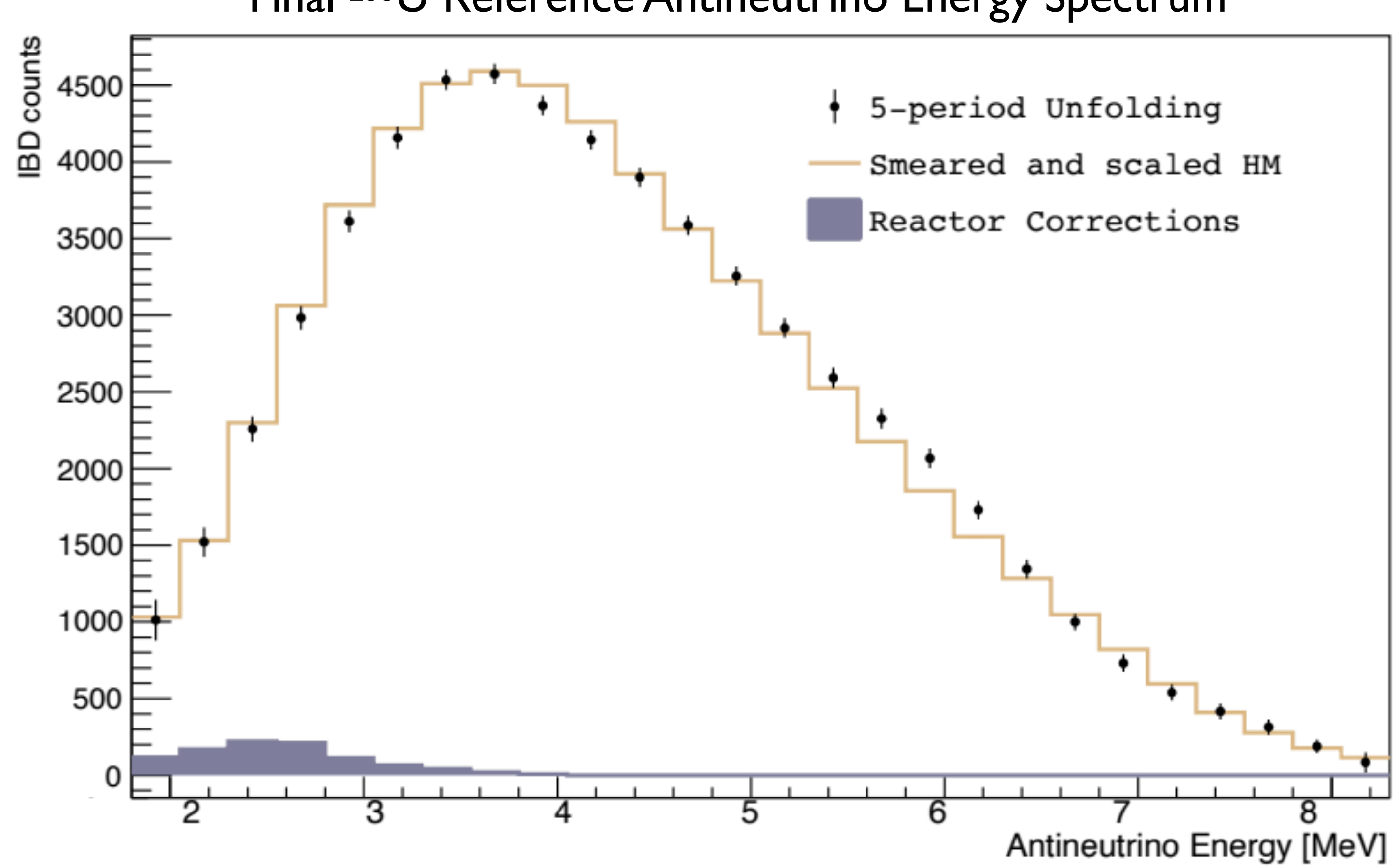
- Develop/demonstrate on-surface IBD detection technology

  NIM A 922 (2018) JINST 13 (2018) JINST 14 P04014 (2019) JINST 14 P03026 (2019) TBD (2023) TBD (2024)

Overburden-Free IBD Detection

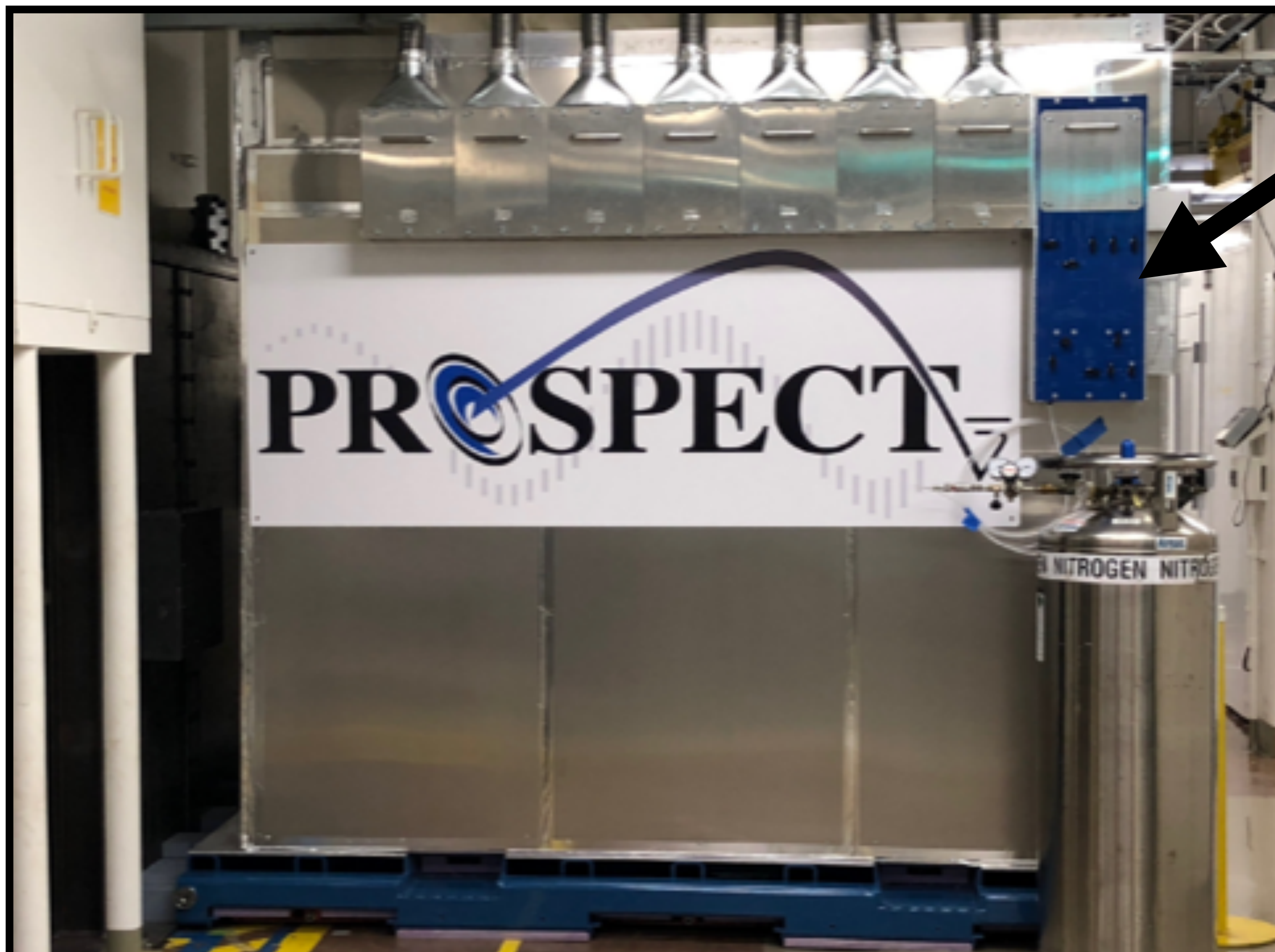


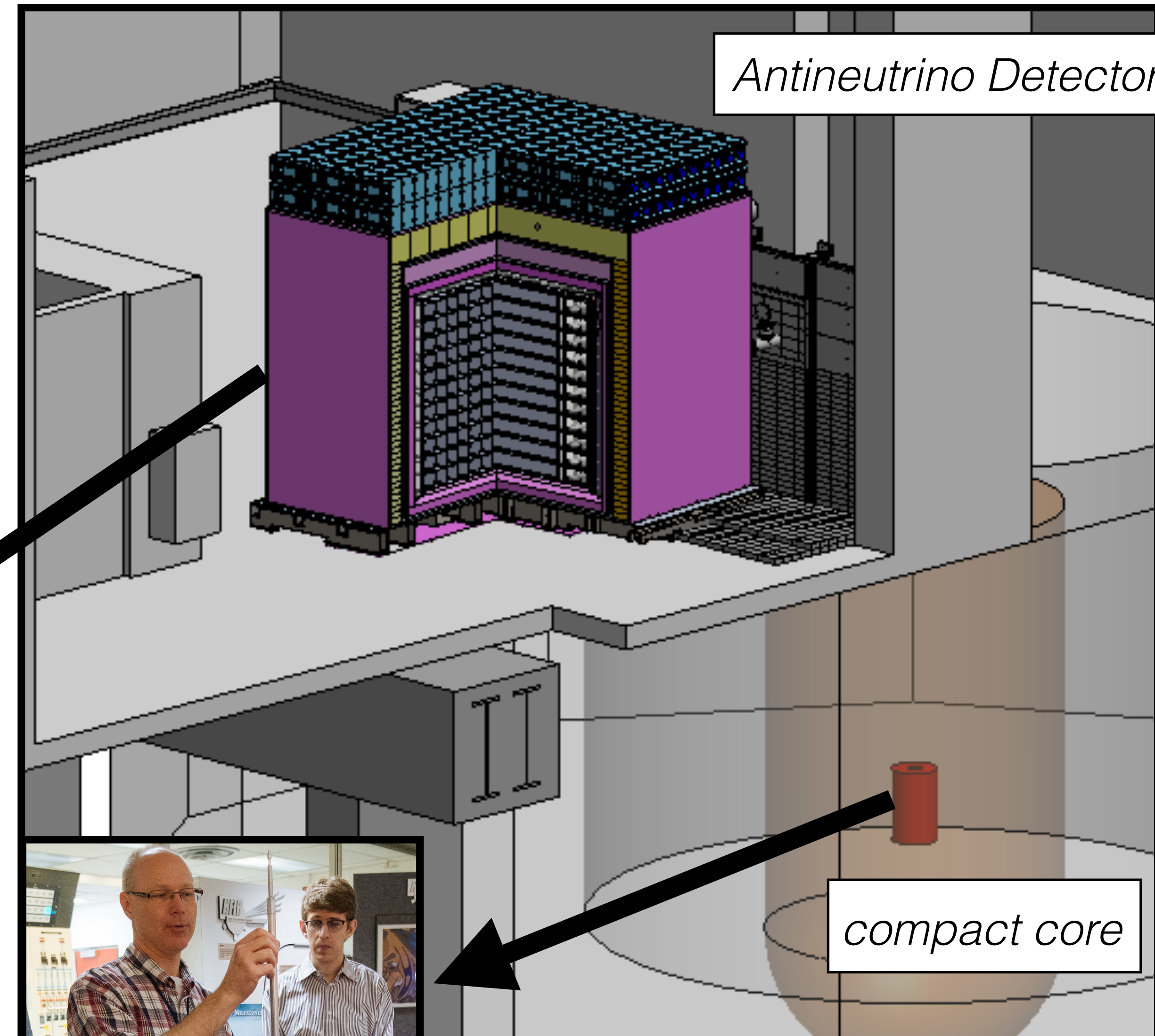
Final ^{235}U Reference Antineutrino Energy Spectrum

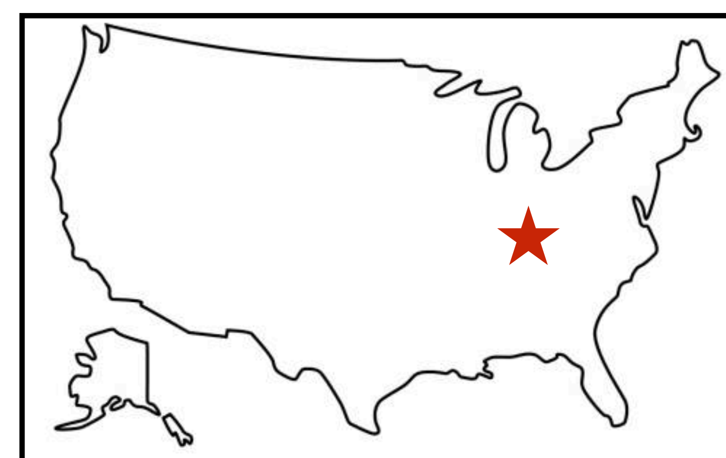


Experimental Layout

- A 4-ton, segmented ^{6}Li-doped PSD LS detector at the HFIR research reactor



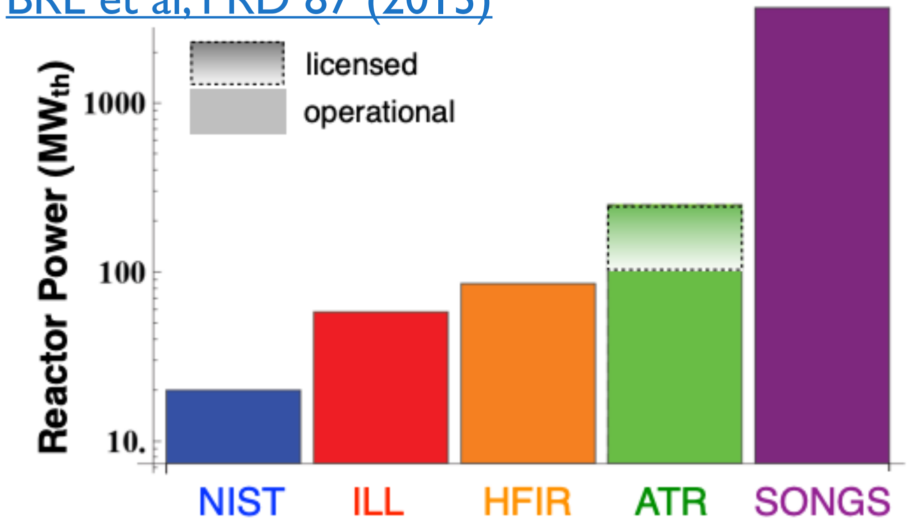


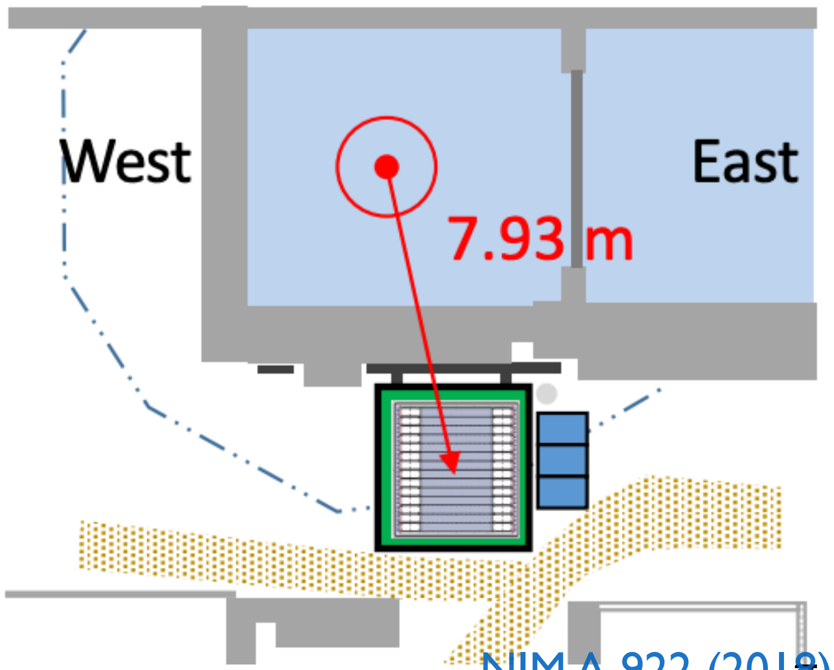


Key HFIR Features

- Reactor:
  - 85 MW core burns only ^{235}U
  - <50cm height, diameter
- Facilities:
  - Many m^2 of floor (~3m wide) 6-10m from core
  - Concrete monolith beneath: high floor loading
  - Adjacent to ground-level exterior doors
- Backgrounds:
  - Lead wall shields gammas from reactor direction
  - Neutron experiments below shielded by monolith
  - <1 mwe overburden: little to no cosmic shielding
- Access:
  - 24/7 data/physical access for authorized personnel
  - HFIR ops rarely (<<1/y) require detector movement

BRL et al, PRD 87 (2013)





NIM A 922 (2018)

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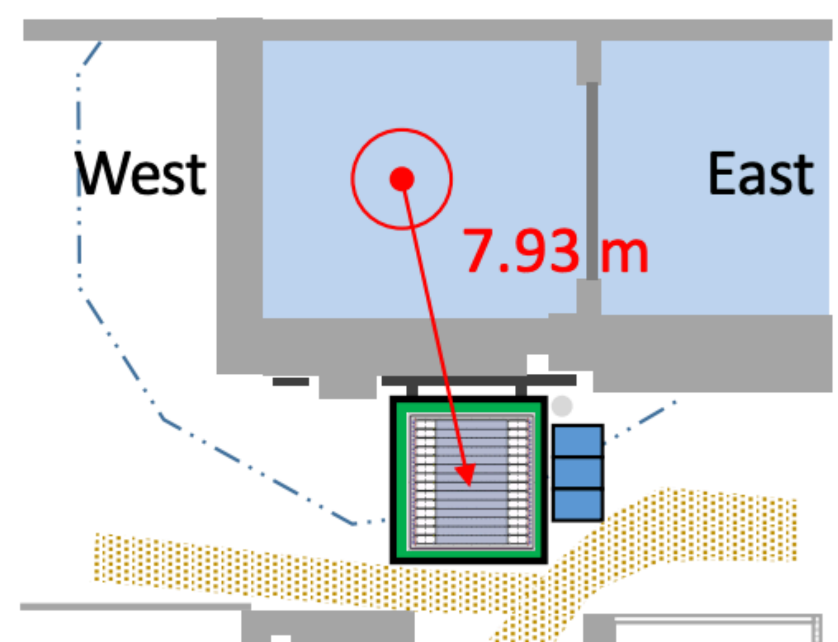
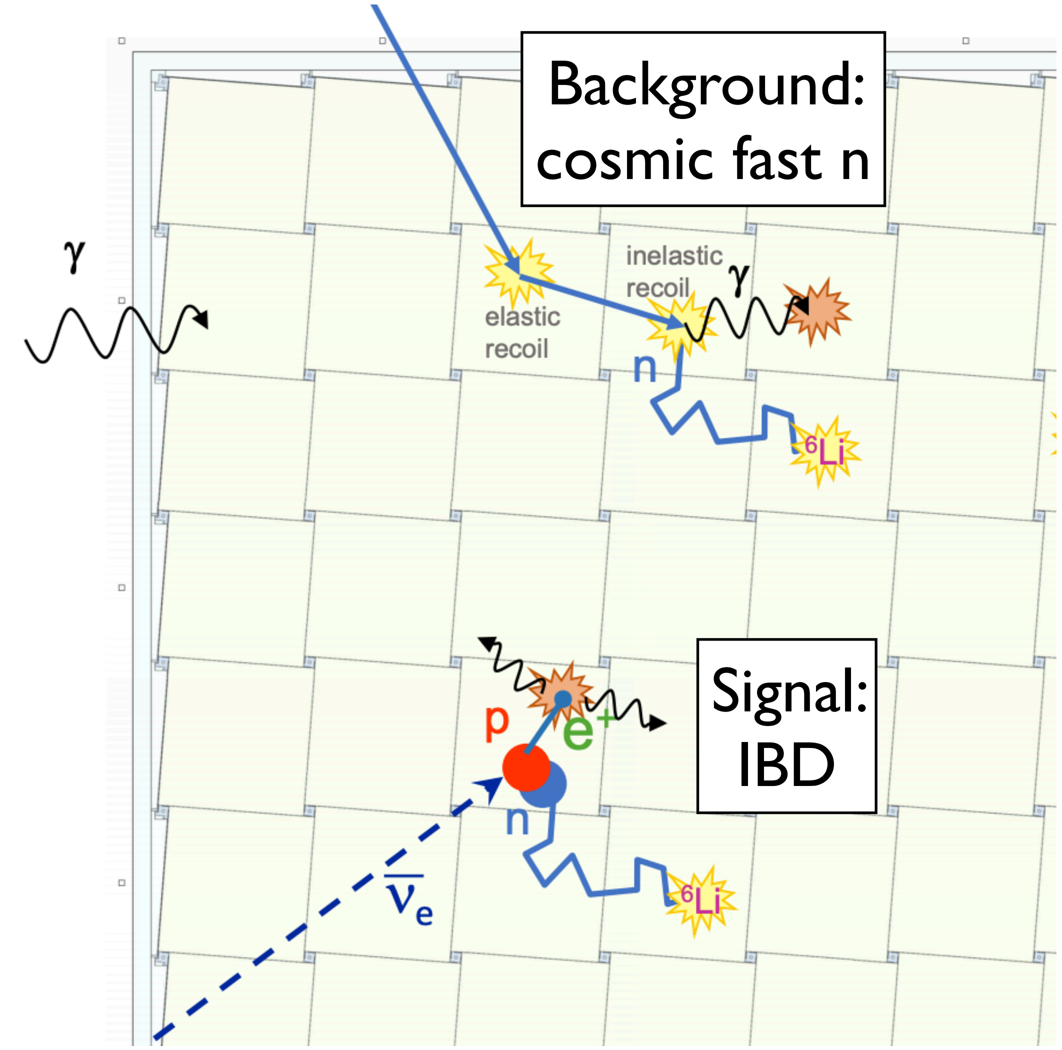
Currently exploring shielding and facility improvements. We will seek community input in the future.



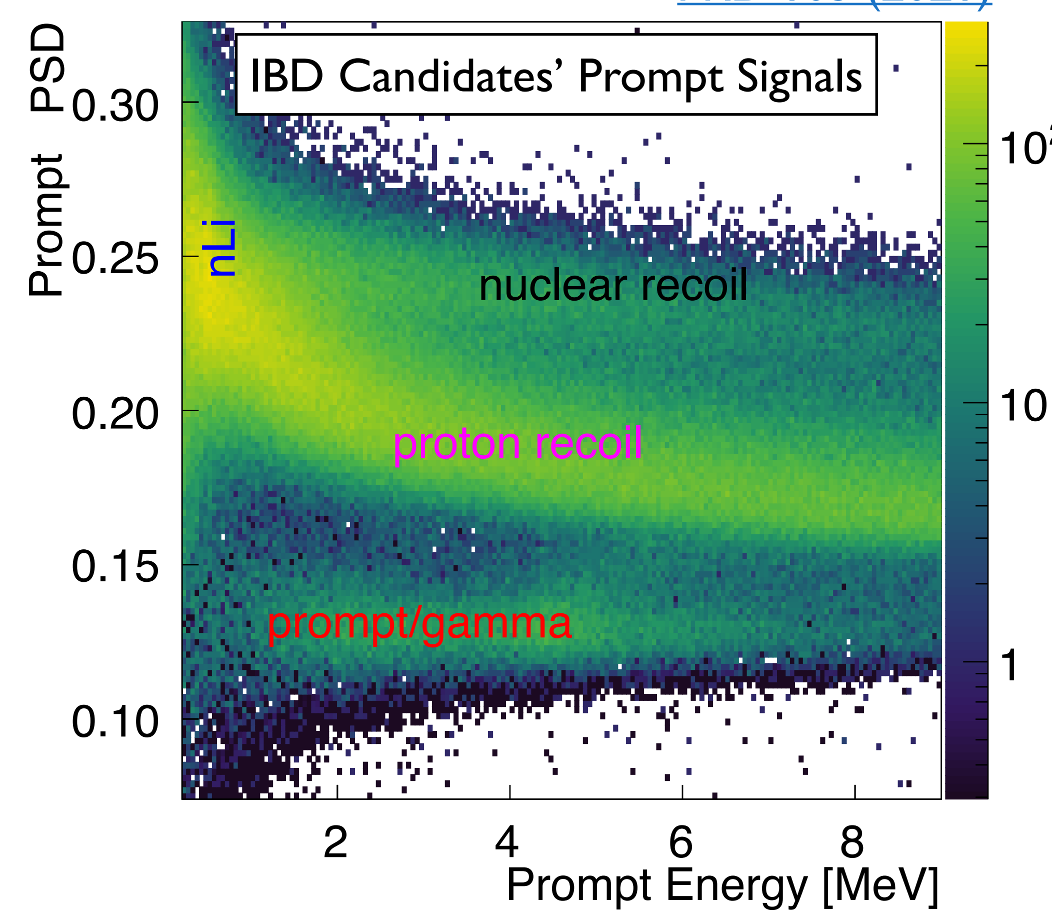
NIM A 922 (2018)

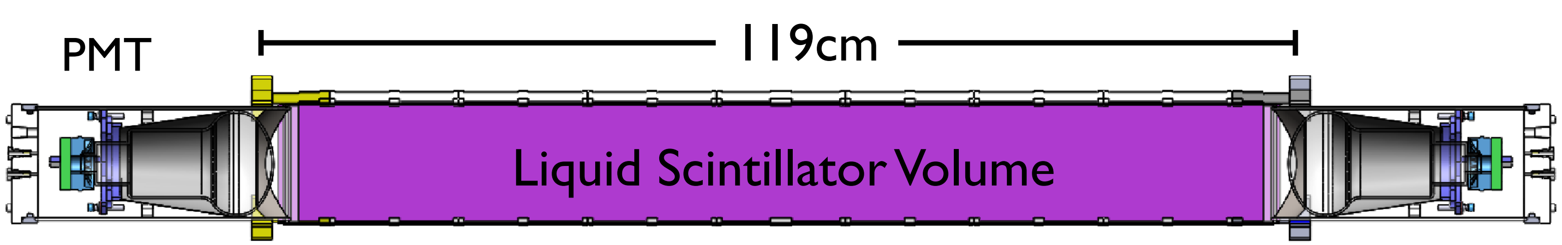
Key Detector Features

- Prompt e^+ gives $\bar{\nu}_e$ energy estimate (>400 pe/MeV)
- Fully-contained, single-cell delayed n-^{6}Li signal
- Prompt, delayed PSD differ from common background classes
- Double-end PMT readout and segmentation allows XYZ reco and topology cuts
- Reactor-on data rates are only manageable with zero-suppression of segments and PMT waveforms!



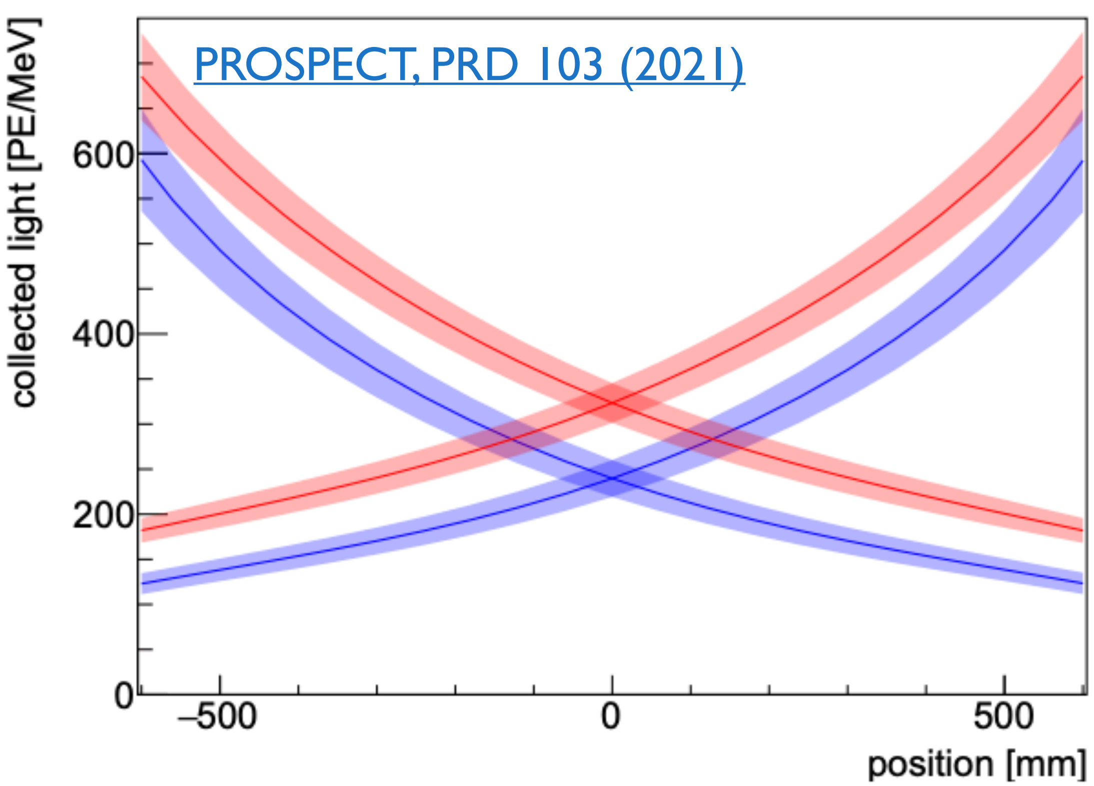
PRD 103 (2021)

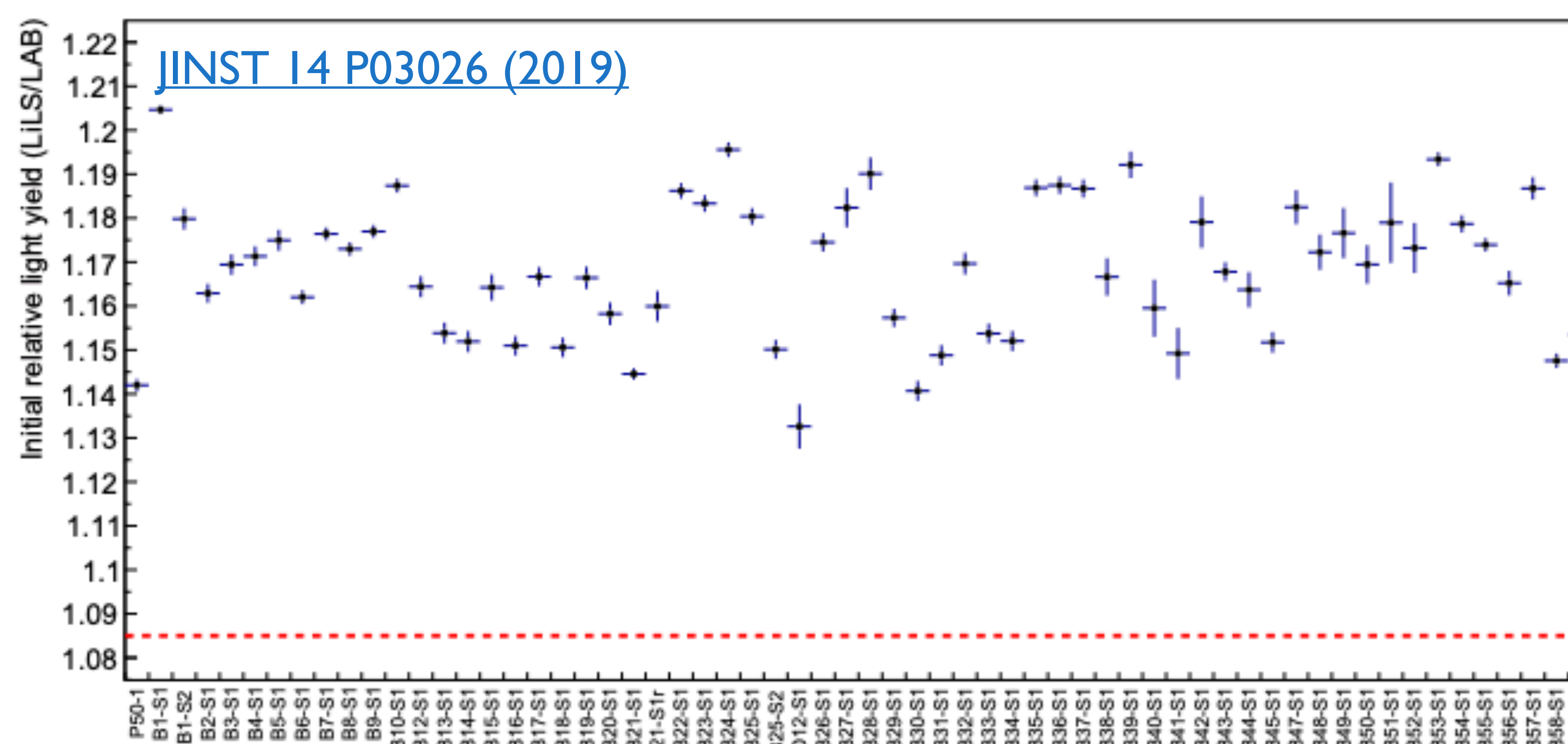




^{6}Li-doped Liquid PSD Scintillator

- **Essential R&D achievement for PROSPECT success: PSD-capable ^{6}Li-loaded LS**
  - BNL-produced formulation based on commercial EJ-309
  - Higher scintillation yield than LAB-based scintillator with PSD (FOM > 2 at 0.53$\mathrm{MeV_{ee}}$ nLi peak)
  - 30% light collection degradation over ~1y physics run; can be improved with better environmental isolation
  - Improved BNL and new LLNL formulations being considered for future PROSPECT efforts

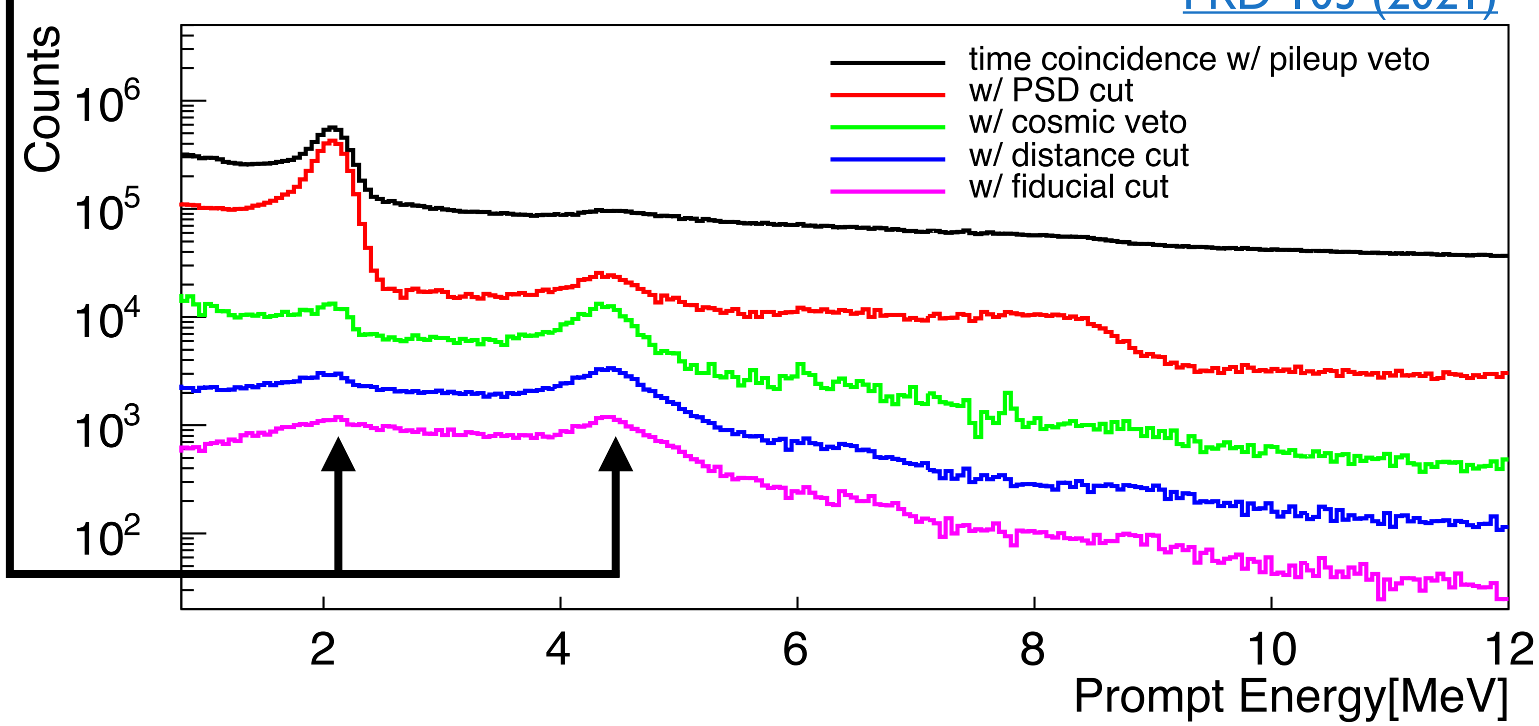




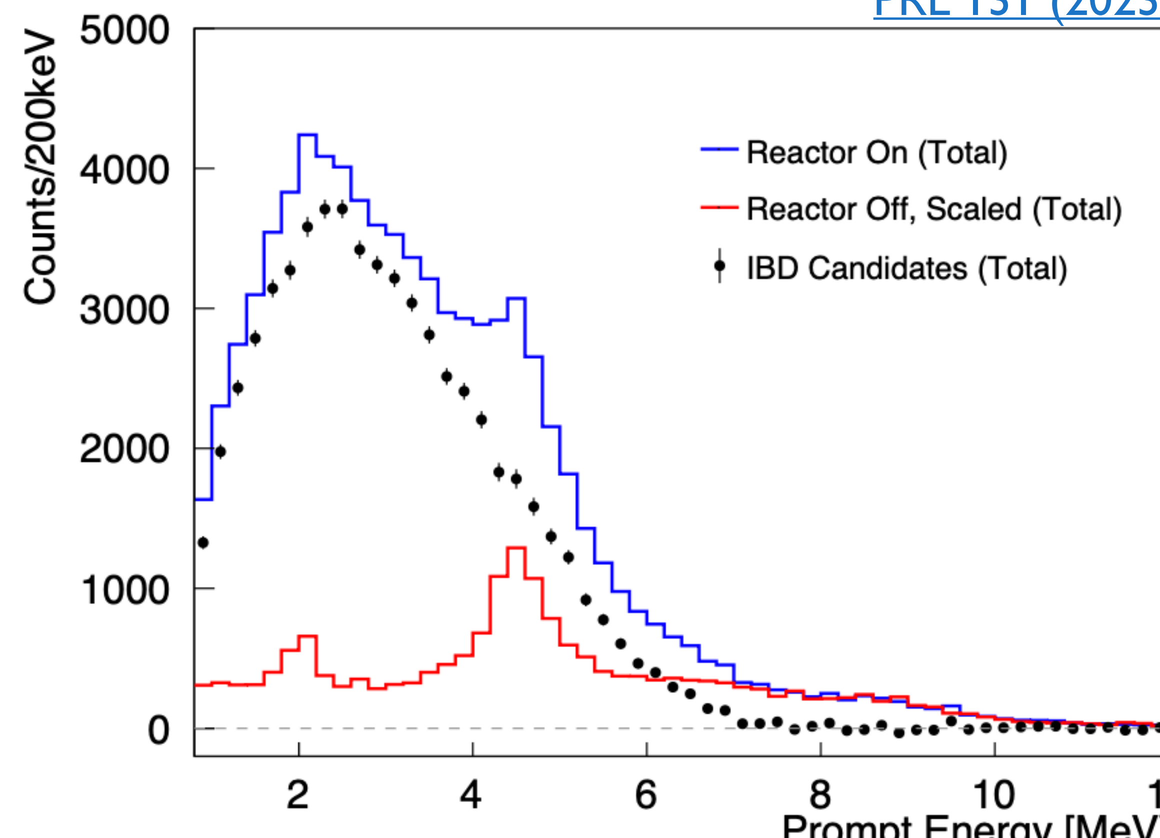
IBD Selection Illustrations

- IBD selection techniques described in last slide enable high signal:background despite near-total lack of overburden
  - S:B >1 at all energies below 6 MeV E_{prompt}, >10:1 for some energies
  - Achieved best-ever S:B for an overburden-free reactor IBD experiment despite an increasing number of non-functioning PMTs during operations
- Remaining backgrounds are dominated by cosmic neutron primaries (no muons, so cannot be easily vetoed)

PRD 103 (2021)



PRL 131 (2023)



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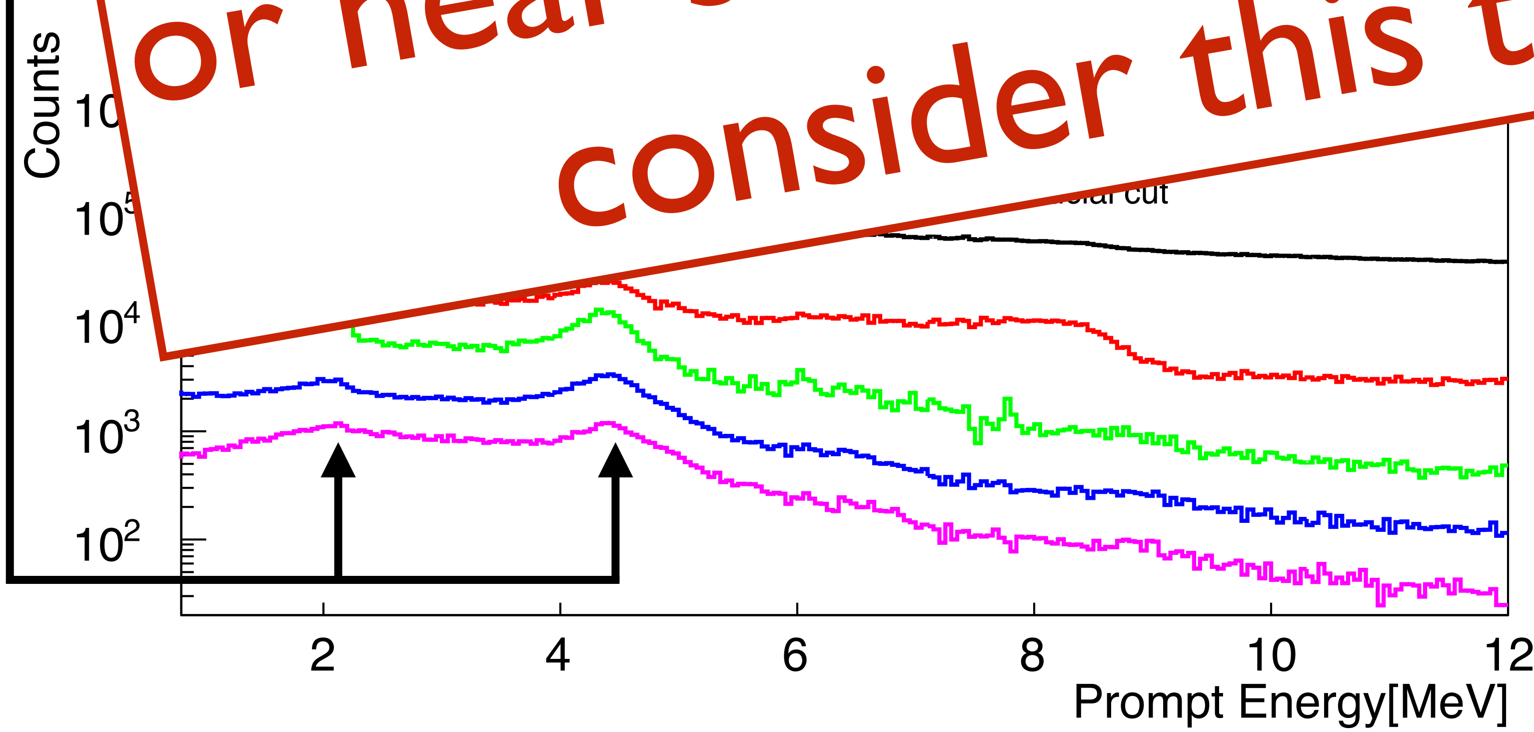
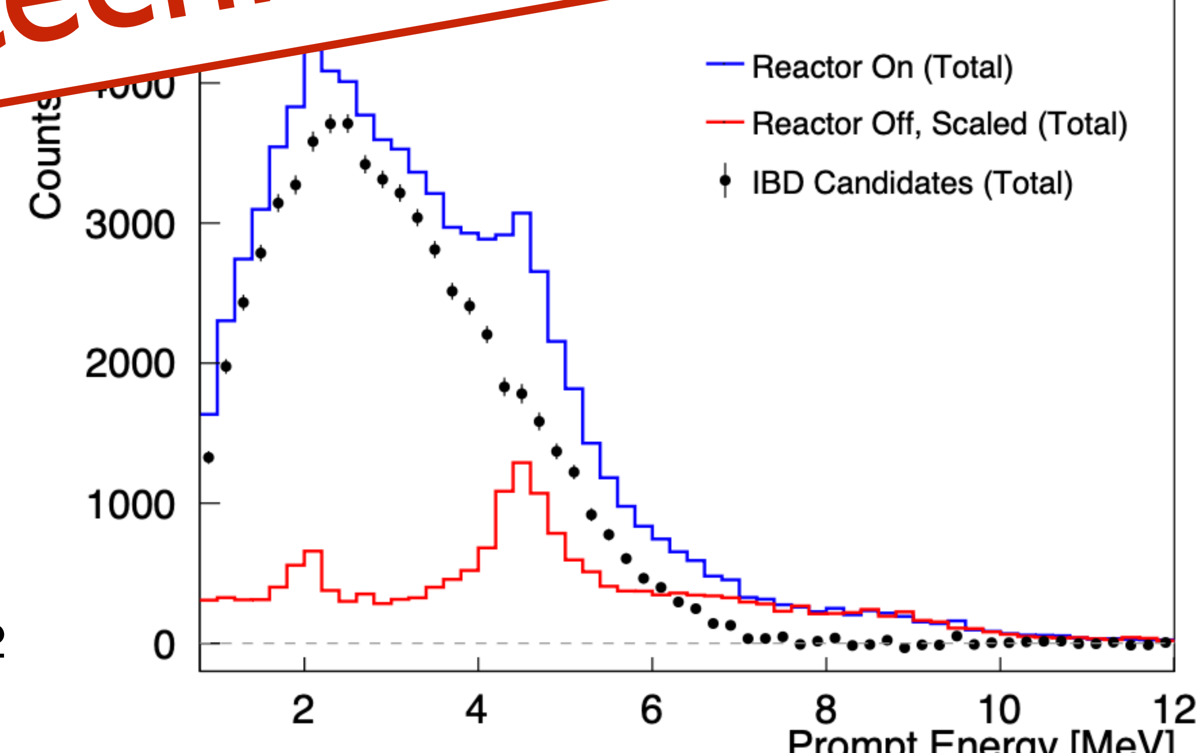
- Remainin...

If you want to make an on-surface or near-surface monitoring detector, consider this technology.

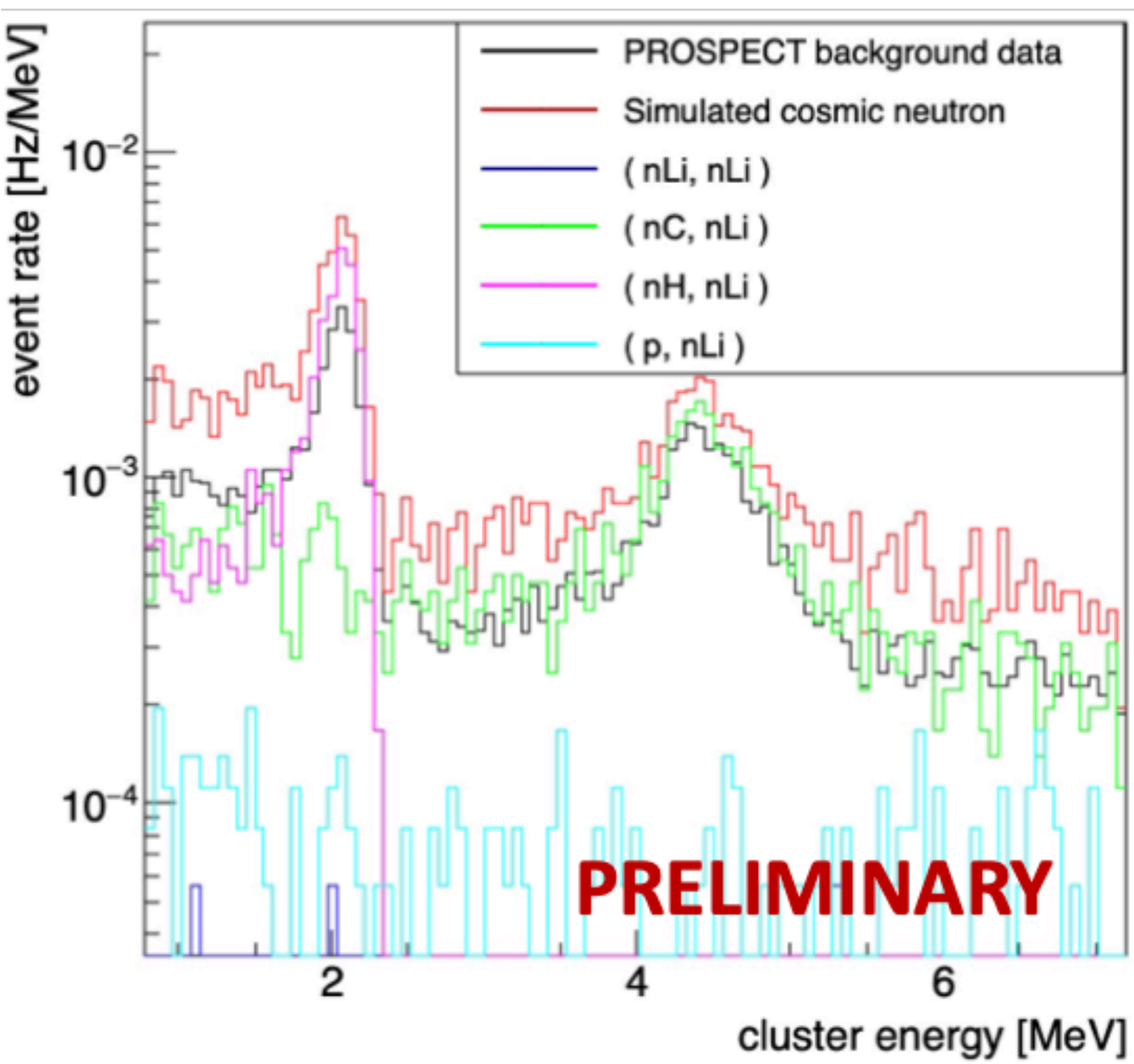
(2023)

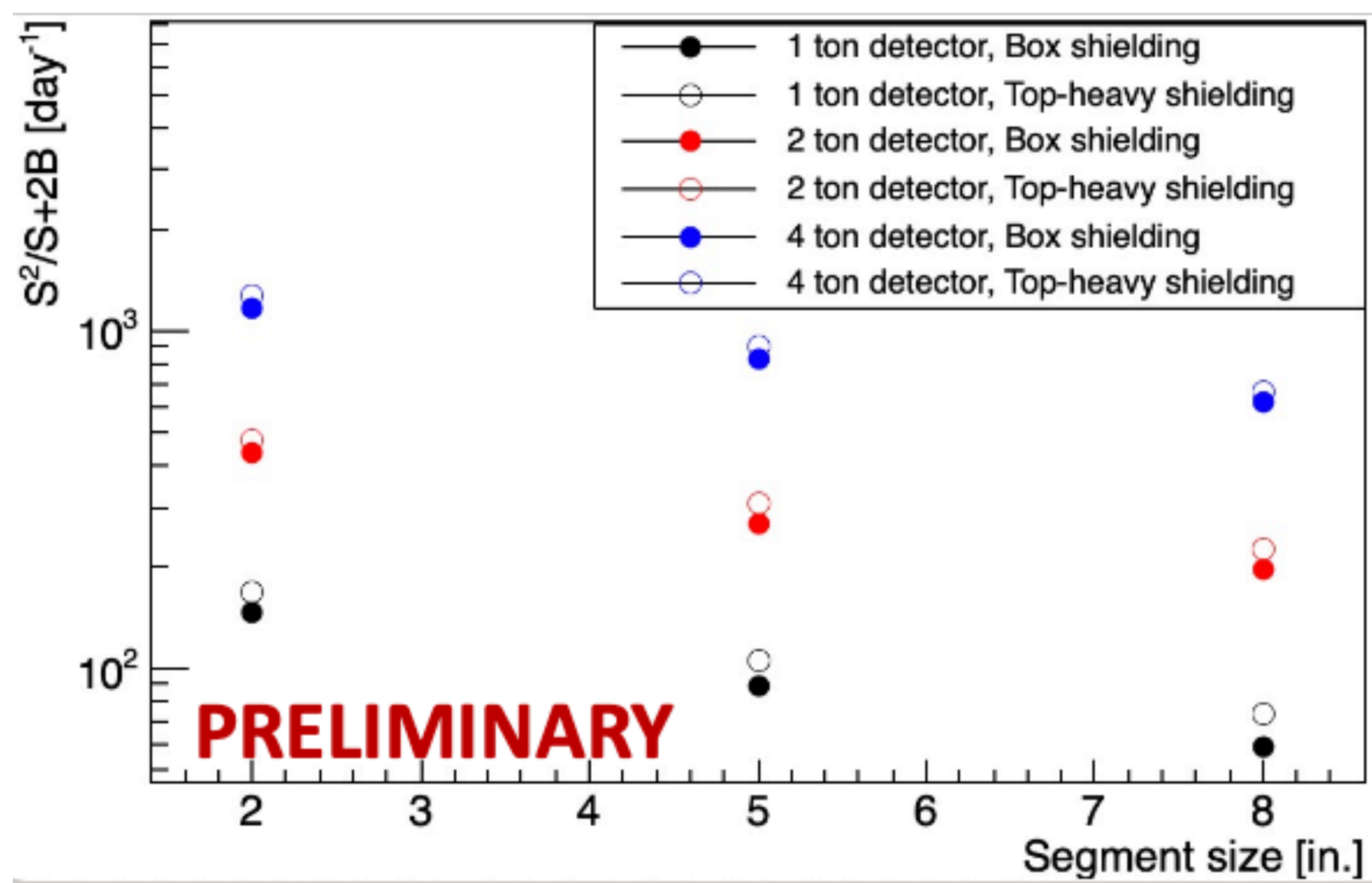




Cosmic Simulations For IBD Detectors

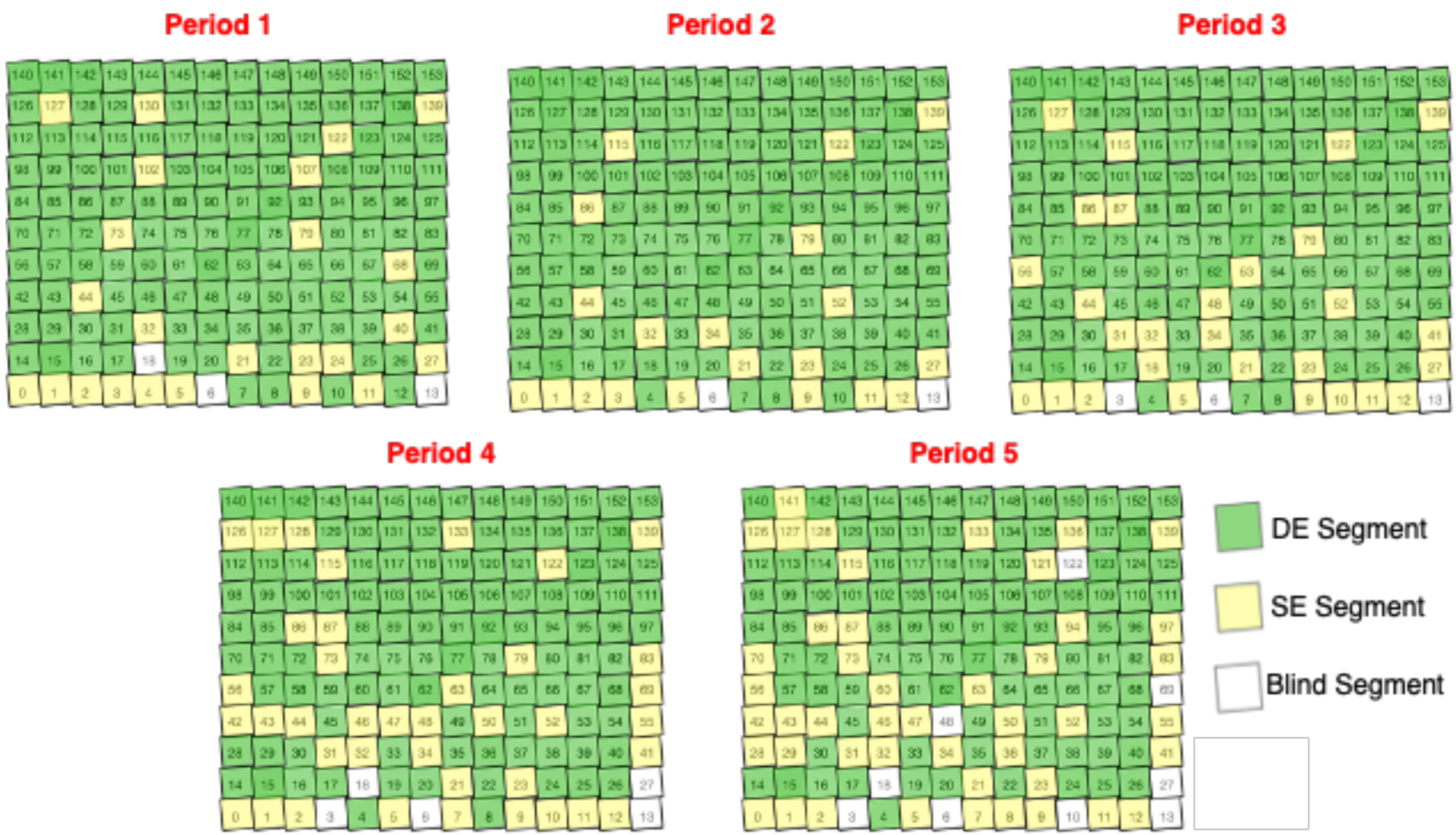
- **PROSPECT developed mature, data-benchmarked cosmic simulation software tailored to reactor IBD experiments**
  - Demonstrates dominance of cosmic neutrons (not muons!) on surface
  - Configurable inputs can be used to optimize many IBD detector types/styles
  - PRApp manuscript in the works (ask us about using this simulation package!)





Results: Final ^{235}U Reference Spectrum

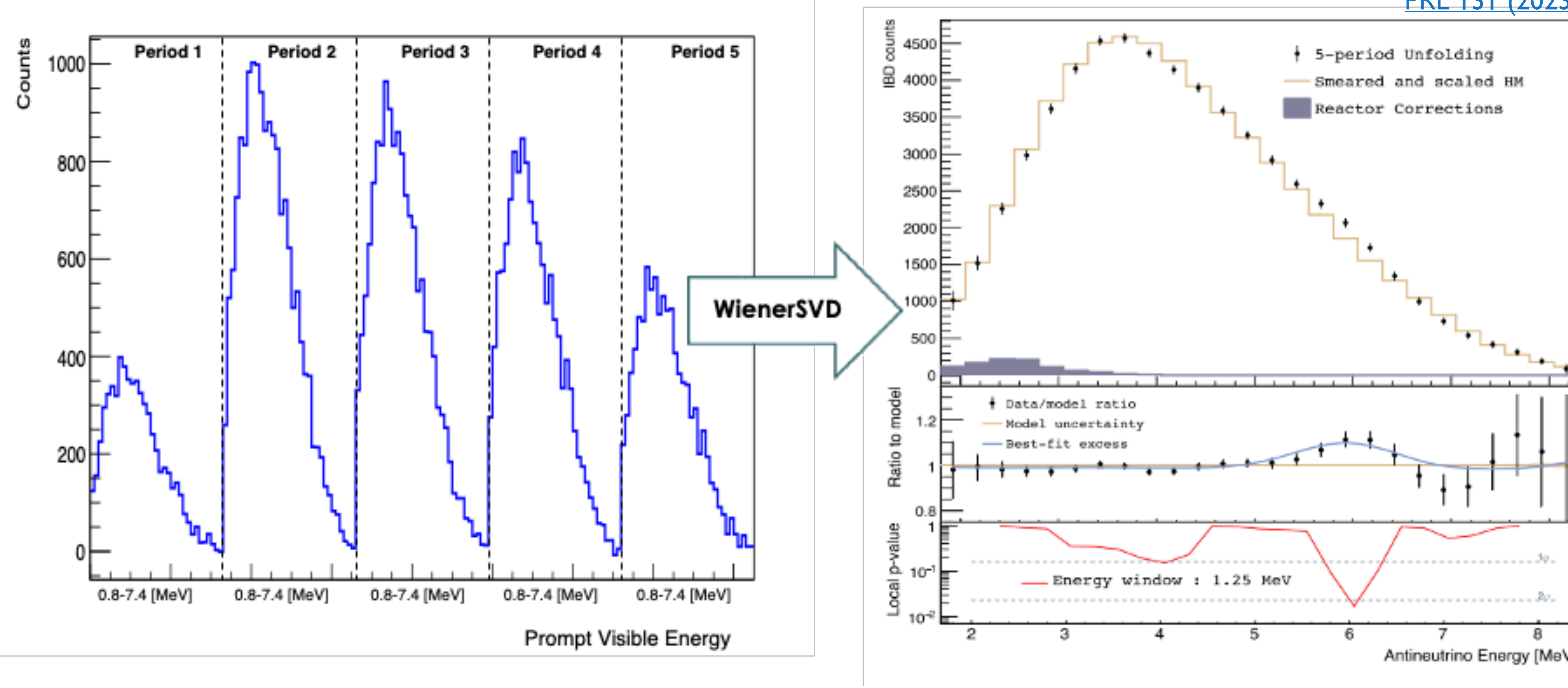
- **For final PROSPECT analyses, we leverages previously-unused data from partially functioning segments**
  - Split the dataset: five periods with different live segment maps
  - Use single-ended segments: their PSD values can reject fast neutron recoils



Results: Final ^{235}U Reference Spectrum

- **Final ^{235}U measurement achieves 2x higher statistical power**
  - New ^{235}U reference spectrum for AAP community is free of potential biases of model inputs (Huber, Summation) or sub-dominant isotopes (Daya Bay)
  - ‘Spectrum Anomaly’ relative to Huber conversion model observed in ^{235}U, now with >3sigma statistical significance

PRL 131 (2023)



Results: Final ^{235}U Reference Spectrum

- Q: Are spectrum data-model disagreements present in all isotopes? Or only some?

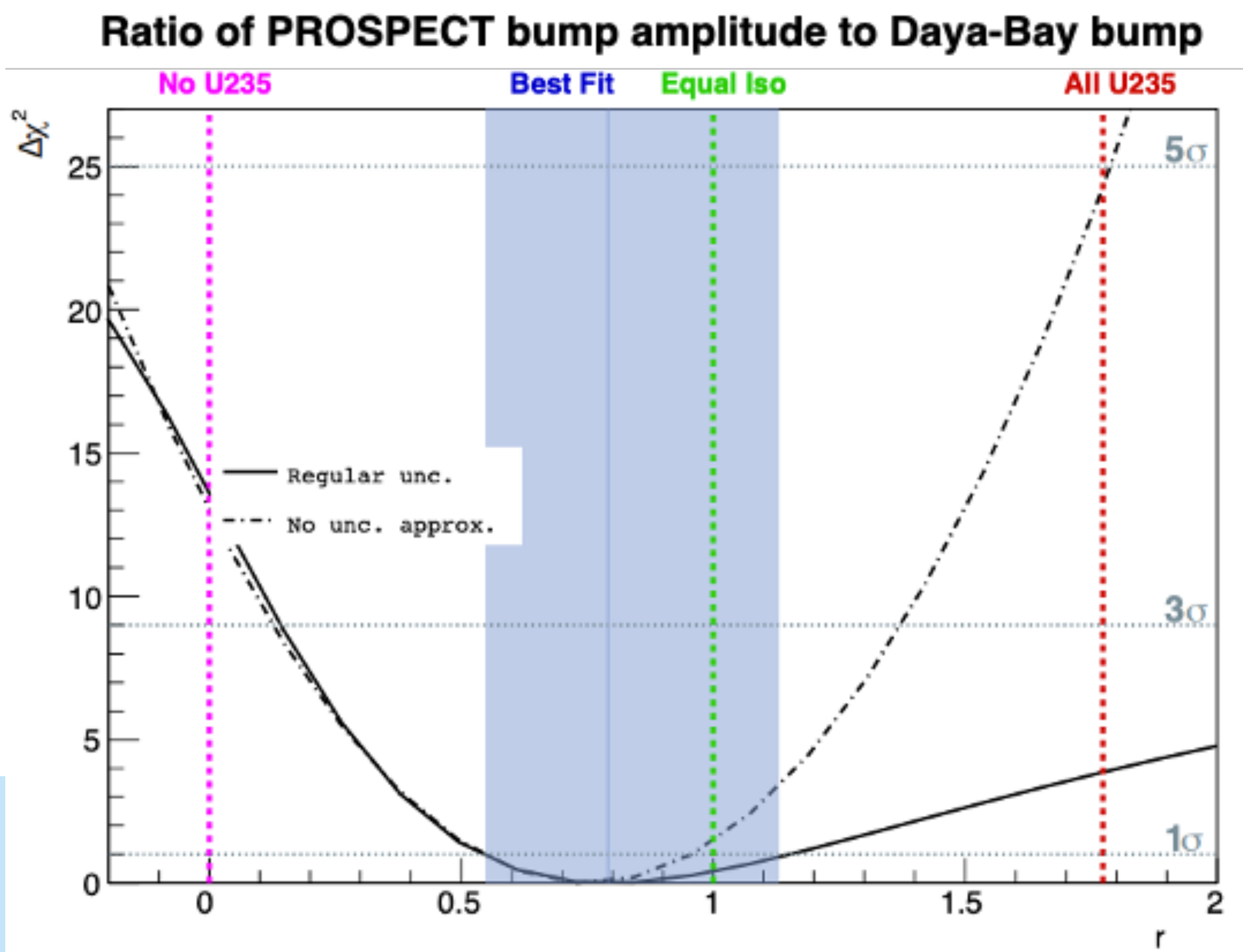
- A: compare bump's amplitude for HEU (PROS) and LEU (DYB)

  - r = 0 (no ^{235}U bump): disfavored at 3.7σ

  - r = 1.78 (Only a ^{235}U bump): disfavored at 2.0σ

  - Detector systematics limit ability to compare LEU and HEU bump sizes (energy scale uncertainties!)

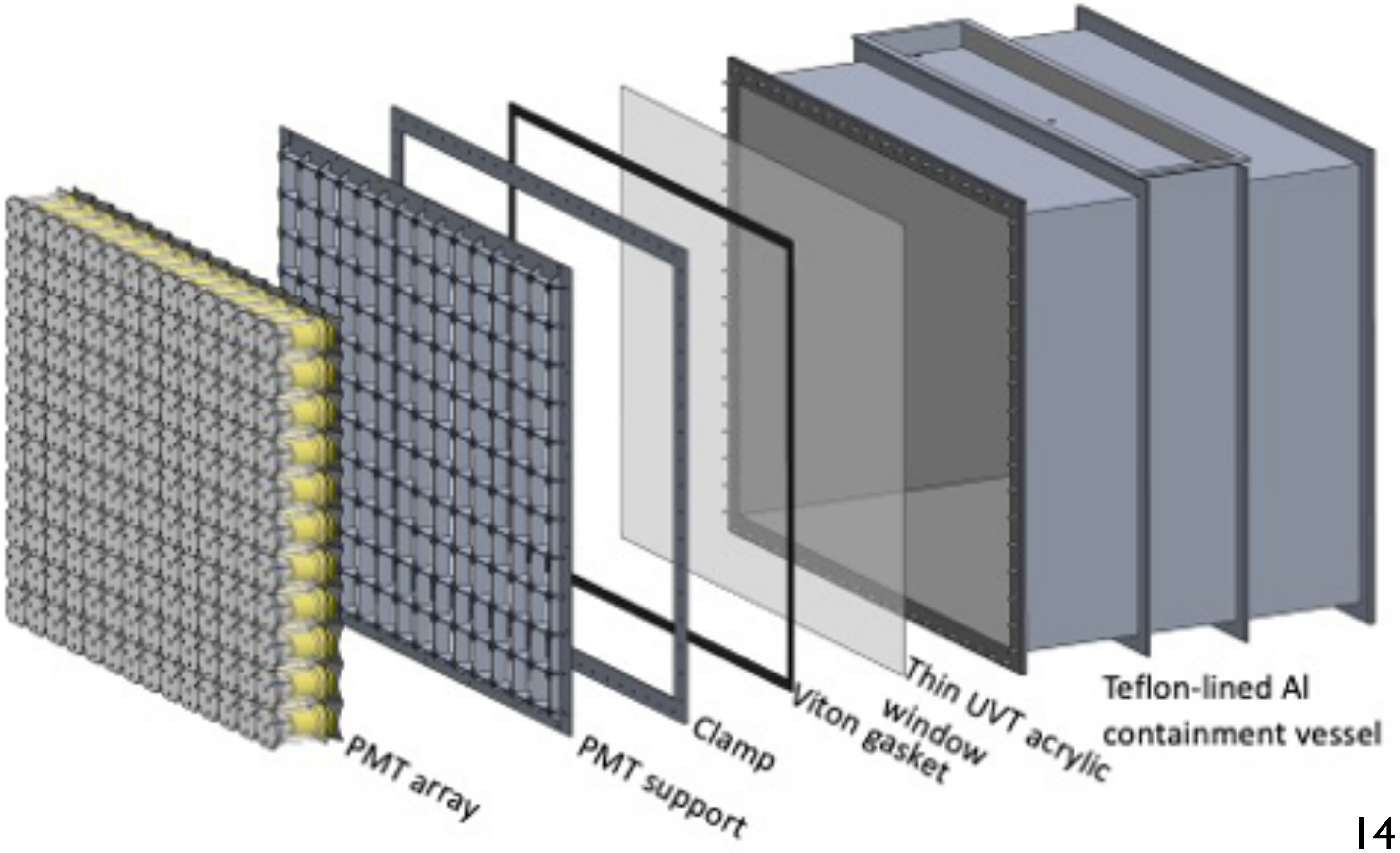
  - If we want to learn more, we must make LEU and HEU measurements with the same detector



Future Steps: PROSPECT-II

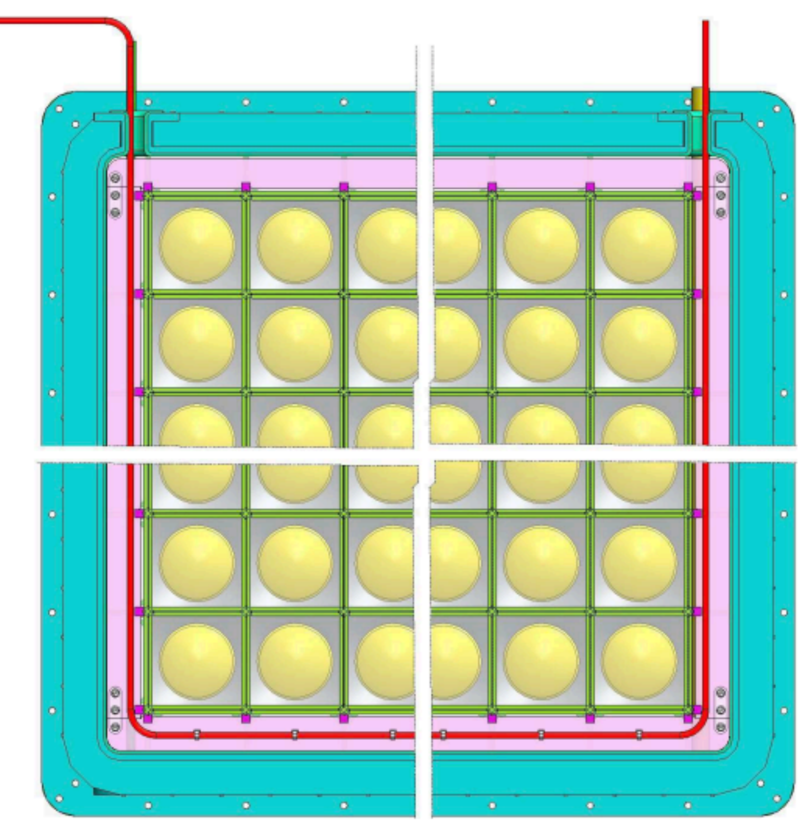
- Performance + stability:
  - Match initial performance (maintain similar pitch, same scintillator formulation, etc.) while improving stability
- Remove PMTs from active volume
  - Eliminates main P-1 failure mode
- Improve environmental control
  - Fewer materials in contact with LiLS
  - Improved cover gas system
  - Active cooling
- Enable emptying/refilling
  - Allows movement to multiple sites, such as HEU+LEU!

Inner detector



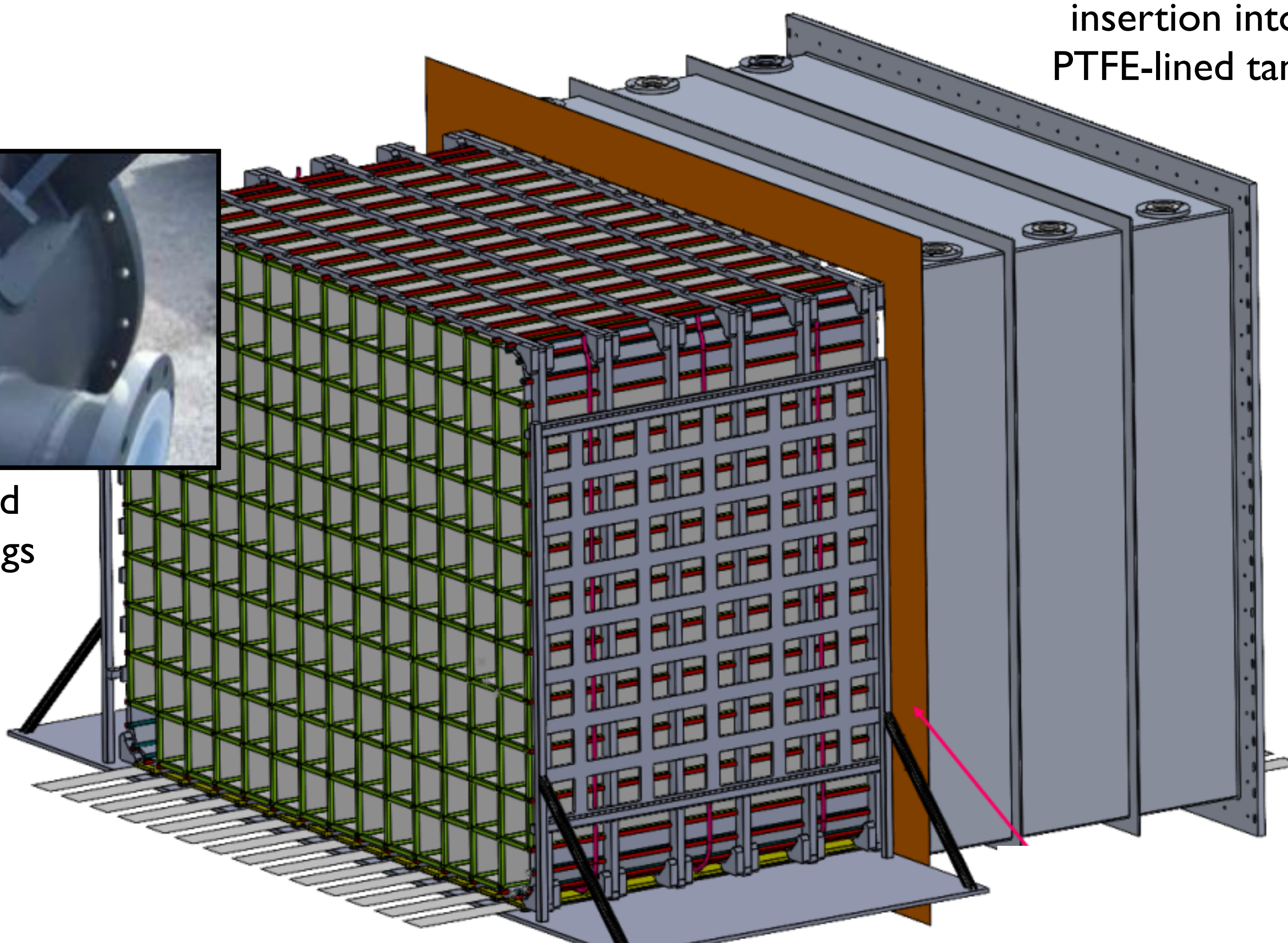
PROSPECT-II R&D Highlights

- Developed/validated external calibration design [JINST 18 P06010 (2023)](#)
- Retired risks associated with segment cross-talk [J Phys G 49 (2022)](#)
- Firming up teflon-lined inner vessel engineering design, procurement with commercial vendors
- Developing integration and assembly procedures
- [Details: P-II IAEA Talk](#)



Segment-external calibration axes

Example: rotolined PTFE flange coatings

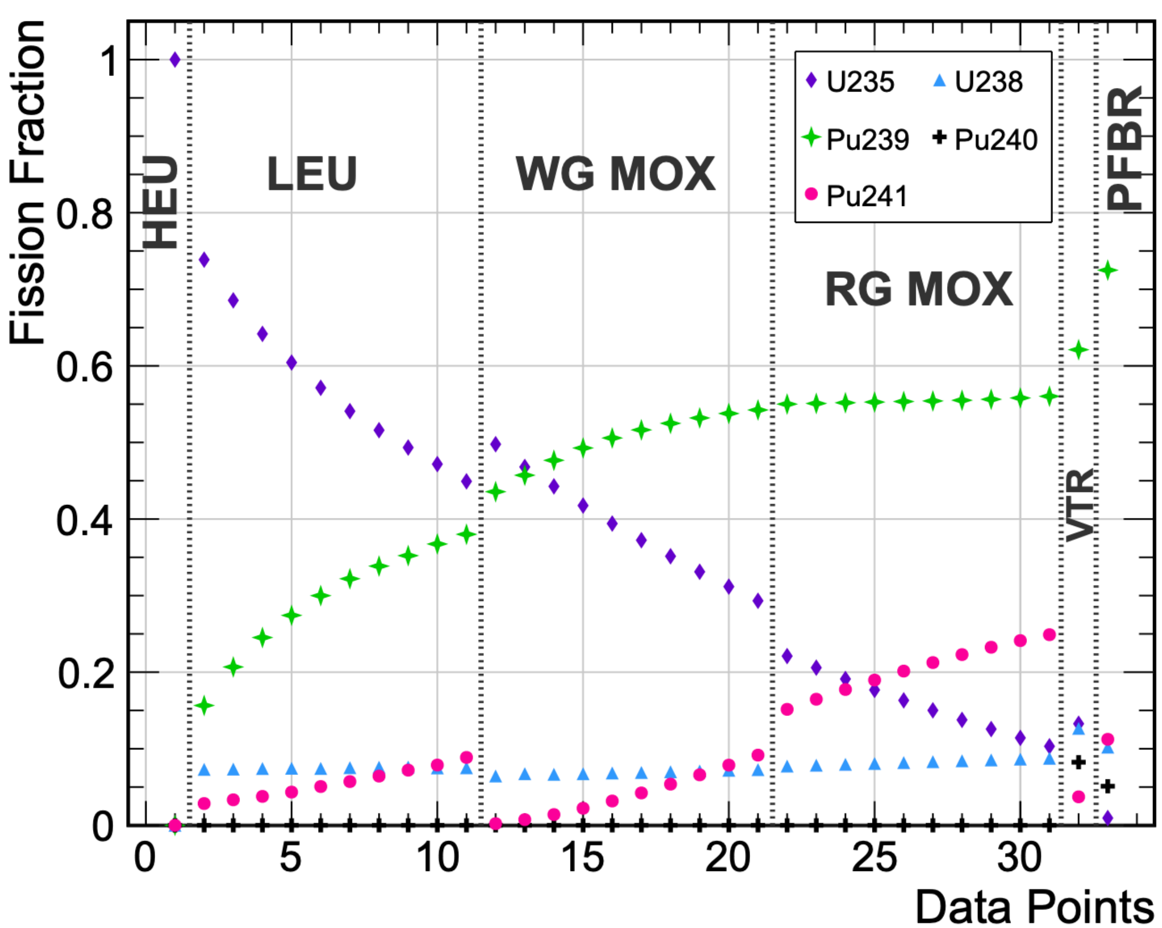


Optical grid insertion into PTFE-lined tank

Multi-Site Physics With PROSPECT-II

- Q: If we deploy one IBD detector at different reactor types, how well can we measure isotopic IBD yields?
  - A: with combined HEU+LEU measurement, four fission isotopes' yields can be measured at 10%-level accuracy (^{241}Pu, ^{238}U) or much better (^{235}U, ^{239}Pu)
  - **JOIN US** in fully developing the (detector-agnostic) physics case for correlated HEU+LEU deployment (isotopic spectra, oscillations, etc)!

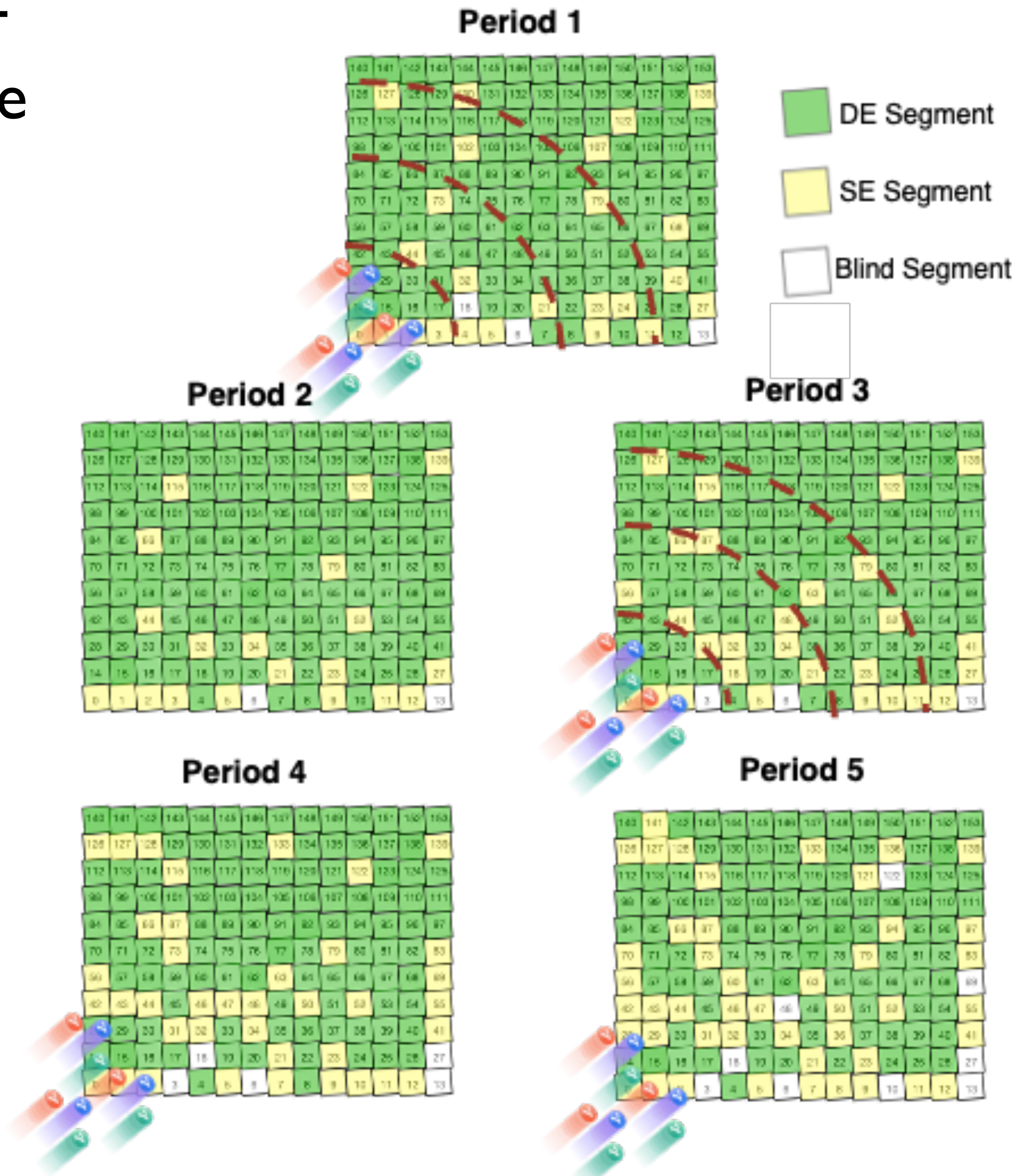
Fujikake, BRL, Rodrigues, Surukuchi, PRD 107 (2023)



Case	Description	Precision on σ_i (%)				
		^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
-	Existing Global Data	1.3	26.4	25.2	-	42.6
1	HEU + LEU	1.6	11.1	4.6	-	10.5
3	HEU + LEU + RG-MOX	1.6	9.7	2.2	-	3.4
2	HEU + LEU + WG-MOX	1.6	9.9	2.5	-	3.6
4	HEU + LEU + Fast	1.6	10.9	4.6	27.2	10.3
5	**All**	**1.6**	**9.5**	**2.1**	**23.6**	**3.3**
6	All, Uncorrelated	1.5	14.3	2.1	36.2	4.2
-	Model Uncertainty [66]	2.1	8.2	2.5	-	2.2

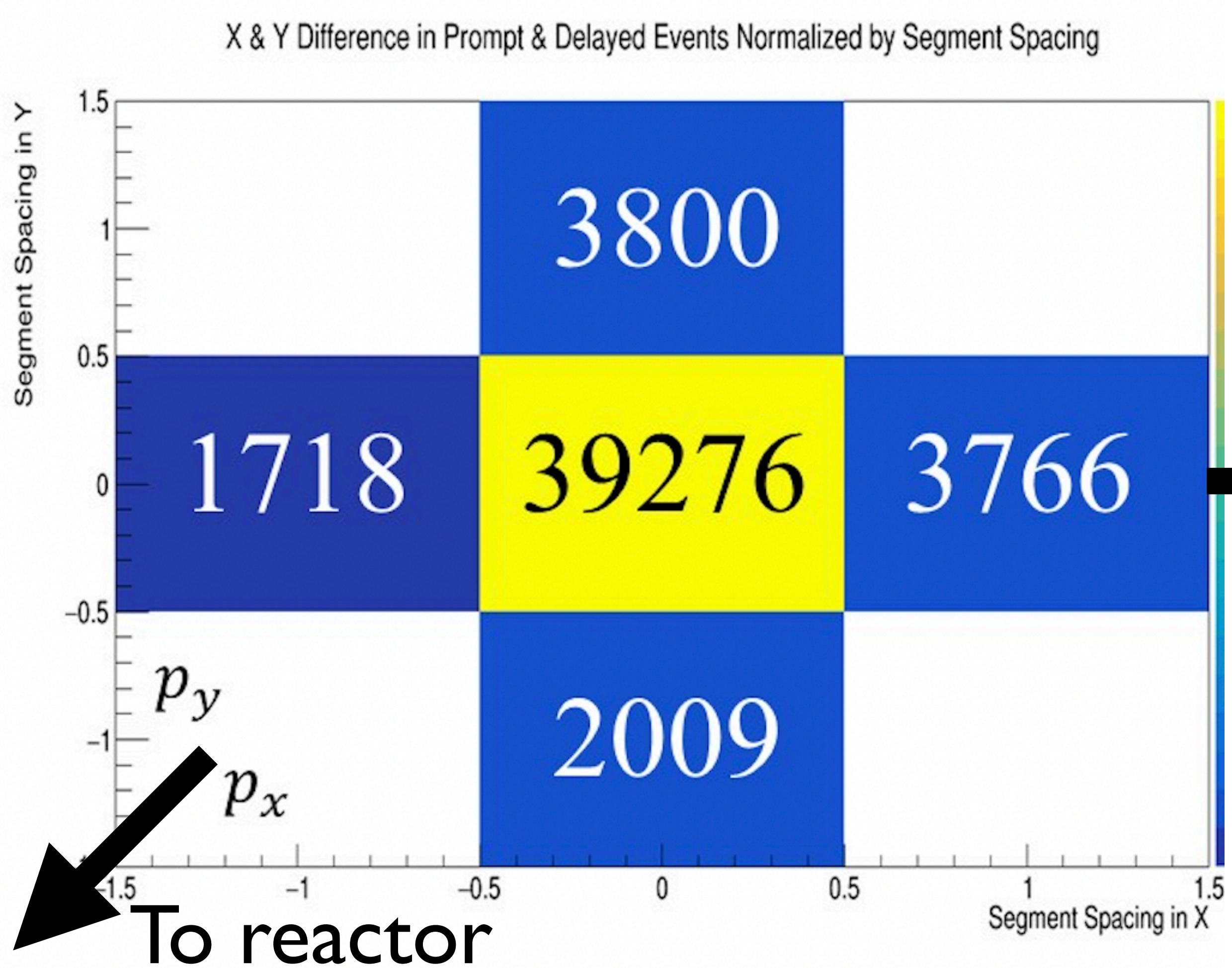
Future: Oscillation in PROSPECT-I

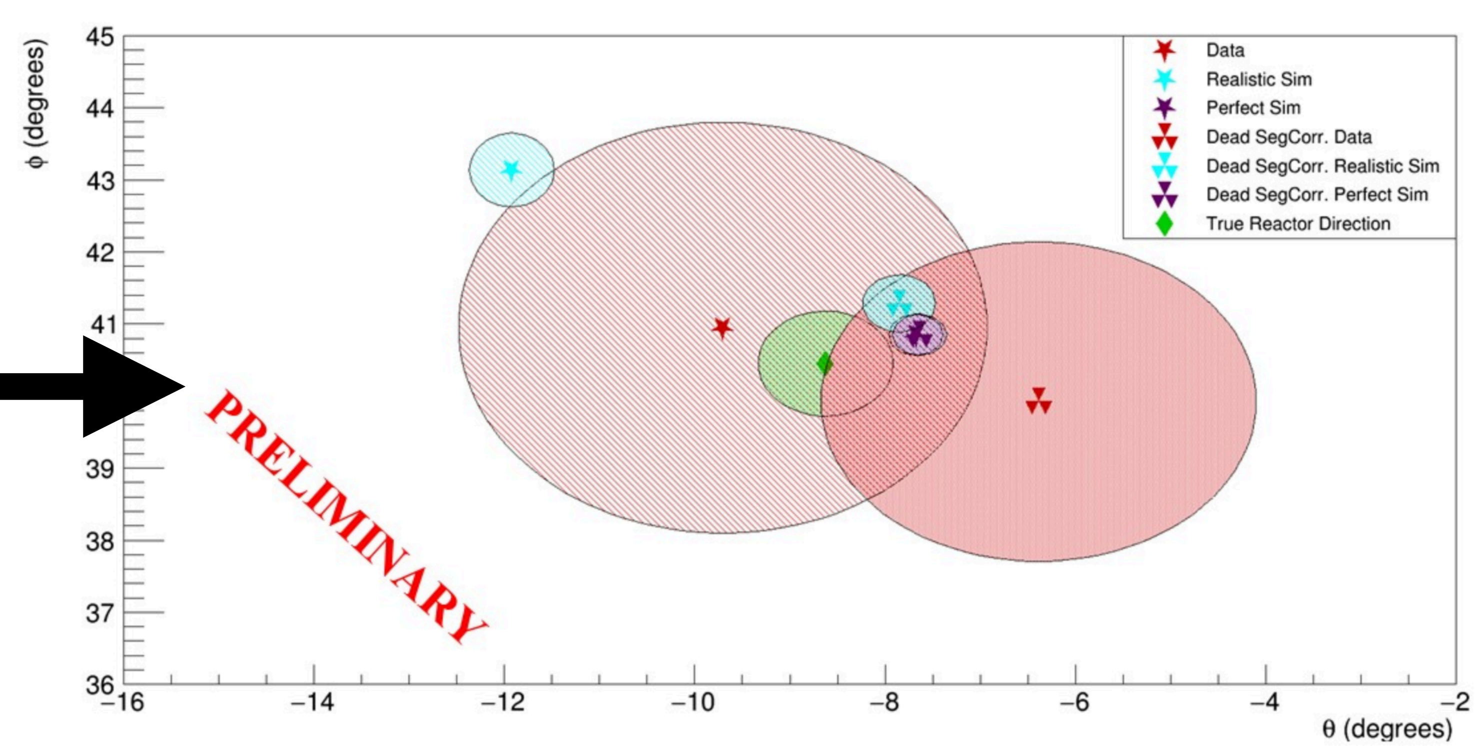
- Final five-period PROSPECT oscillation search will feature ~x2 improved sensitivity
- Expect a final PROSPECT sterile search in 2023
- Working towards a joint analysis using final datasets from PROSPECT, STEREO, and Daya Bay



Future: Directionality in PROSPECT-I

- Downstream segments see substantially more IBD neutrons
- Effect is predicted by IBD MC properly taking into account the direction of neutrino propagation
- Analysis underway to quantify pointing capability of a PROSPECT-style detector: expect a publication in 2023-2024.





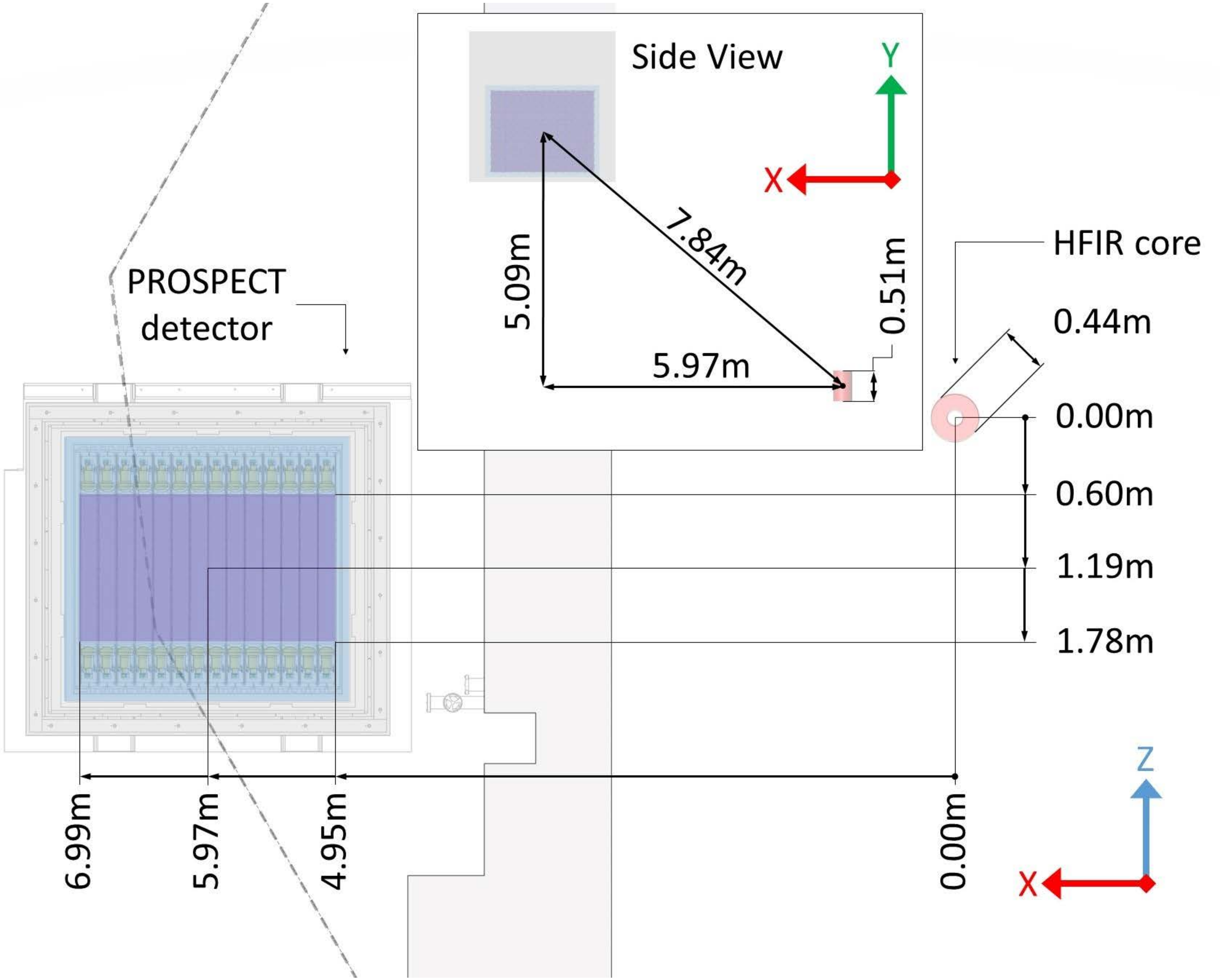
Conclusions and PROSPECTs

- PROSPECT has demonstrated >>1 S:B in an overburden-free reactor IBD experiment: a major achievement for AAP
- Along the way, we've developed tech, tools, and knowledge:
  - Leading sterile oscillation limits and reference ^{235}U spectra
  - Li-doped PSD-capable LiLS and supporting IBD detector design concepts
  - Versatile and reliable cosmic background simulations
  - A user-friendly US-based reactor neutrino lab at HFIR
- Working towards a multi-site deployment of PROSPECT-II

PROSPECT June 2023 Collaboration Meeting, IIT+Virtual

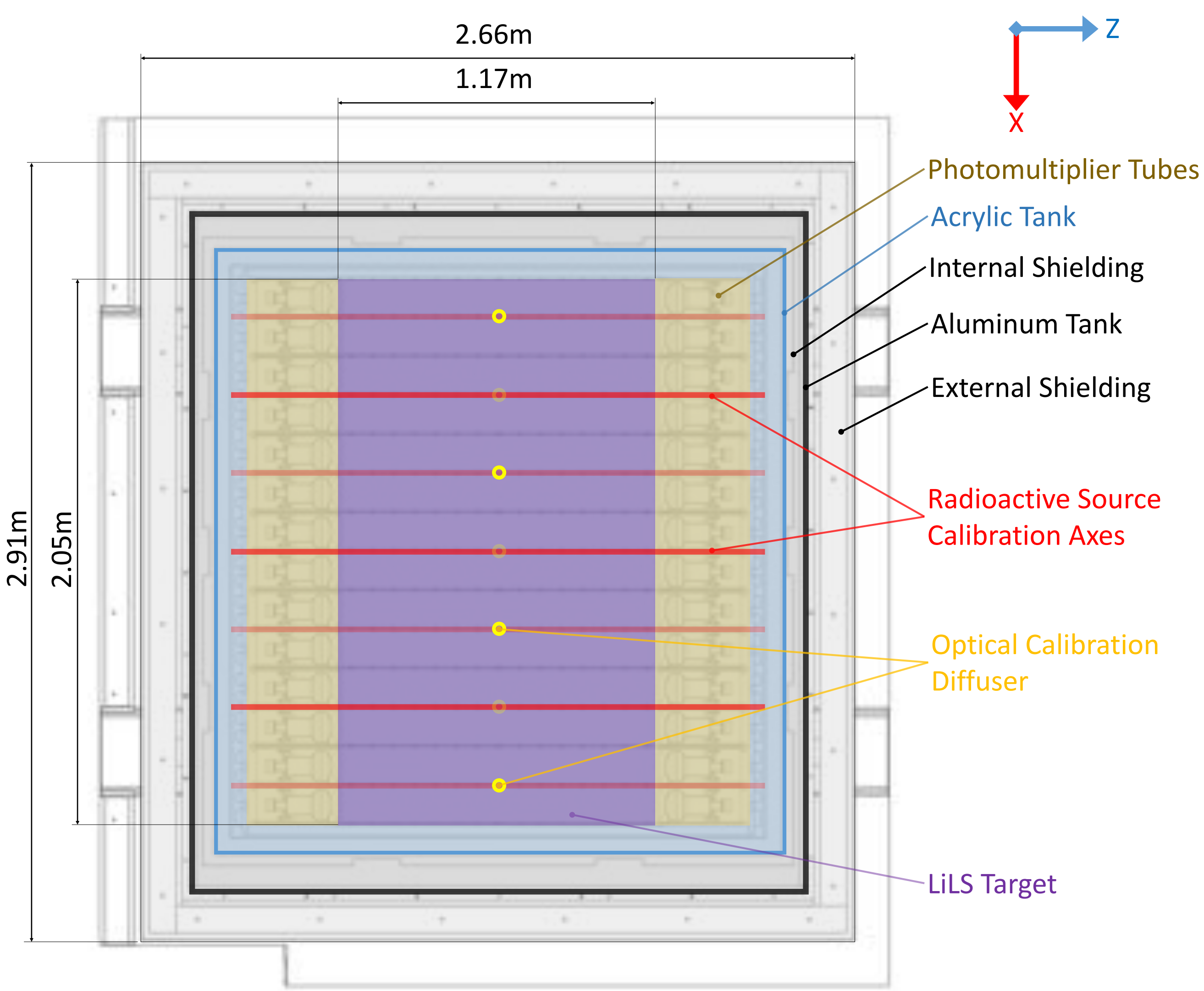
Backup

Experimental Layout

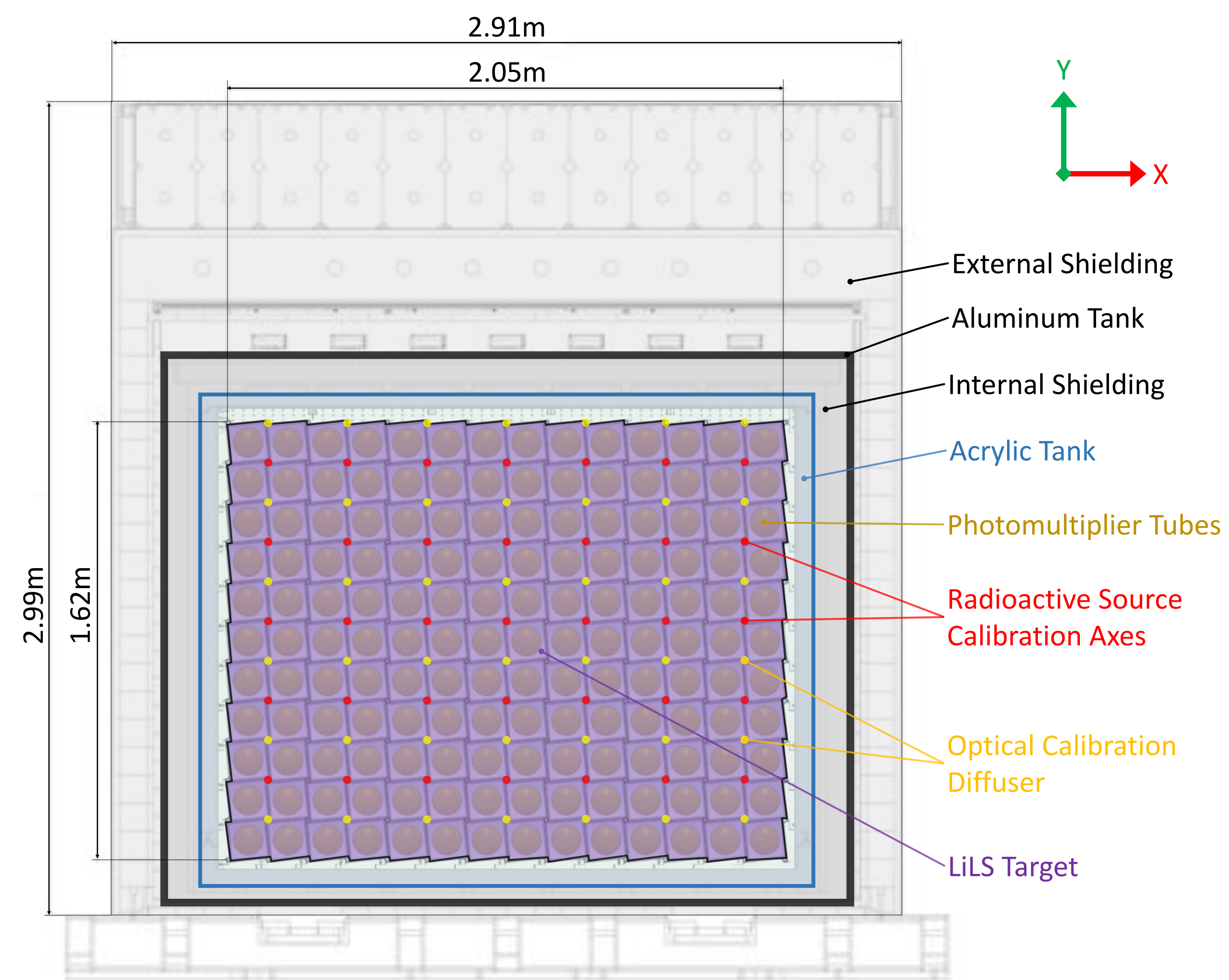


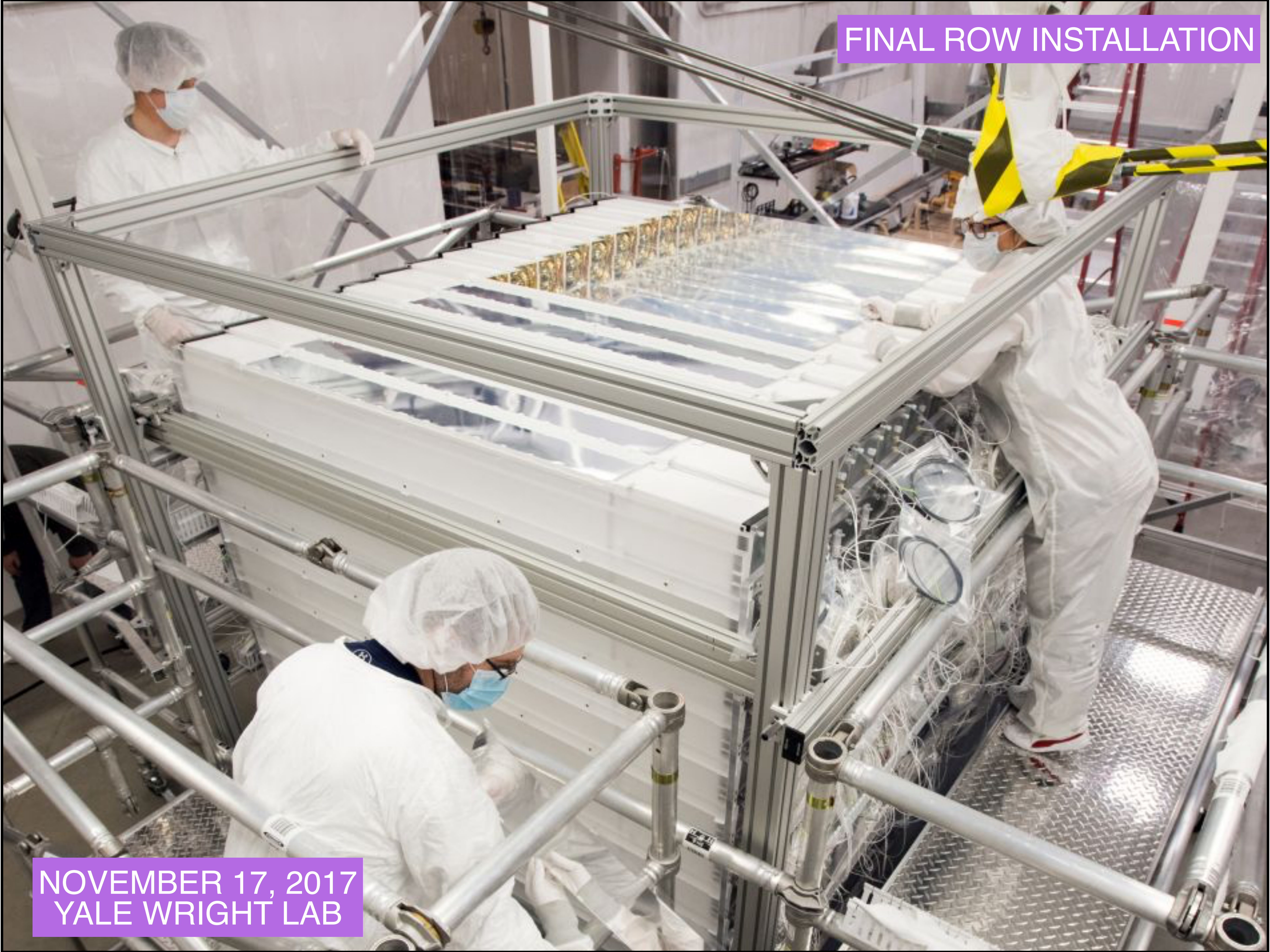
Detector Layout

Top View



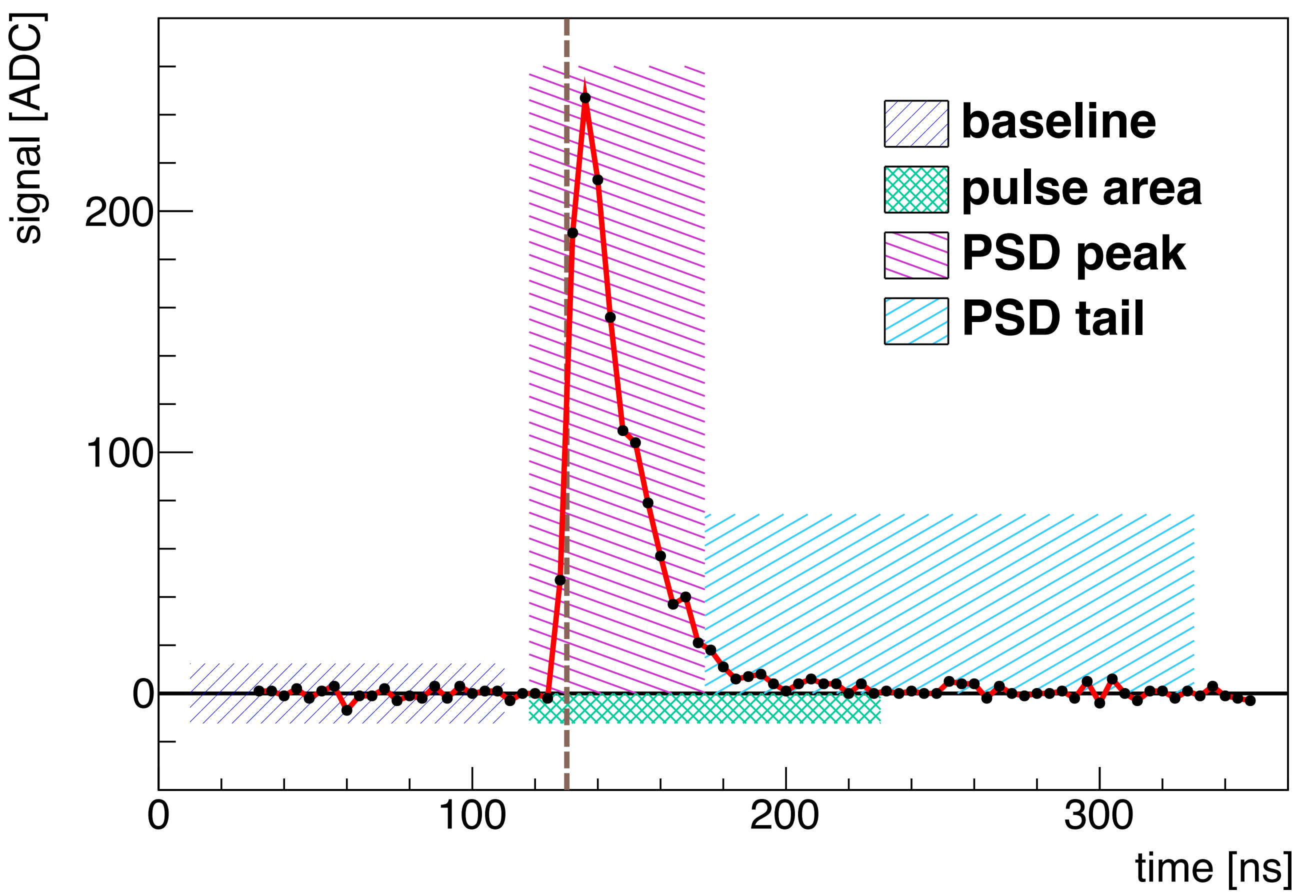
Side View

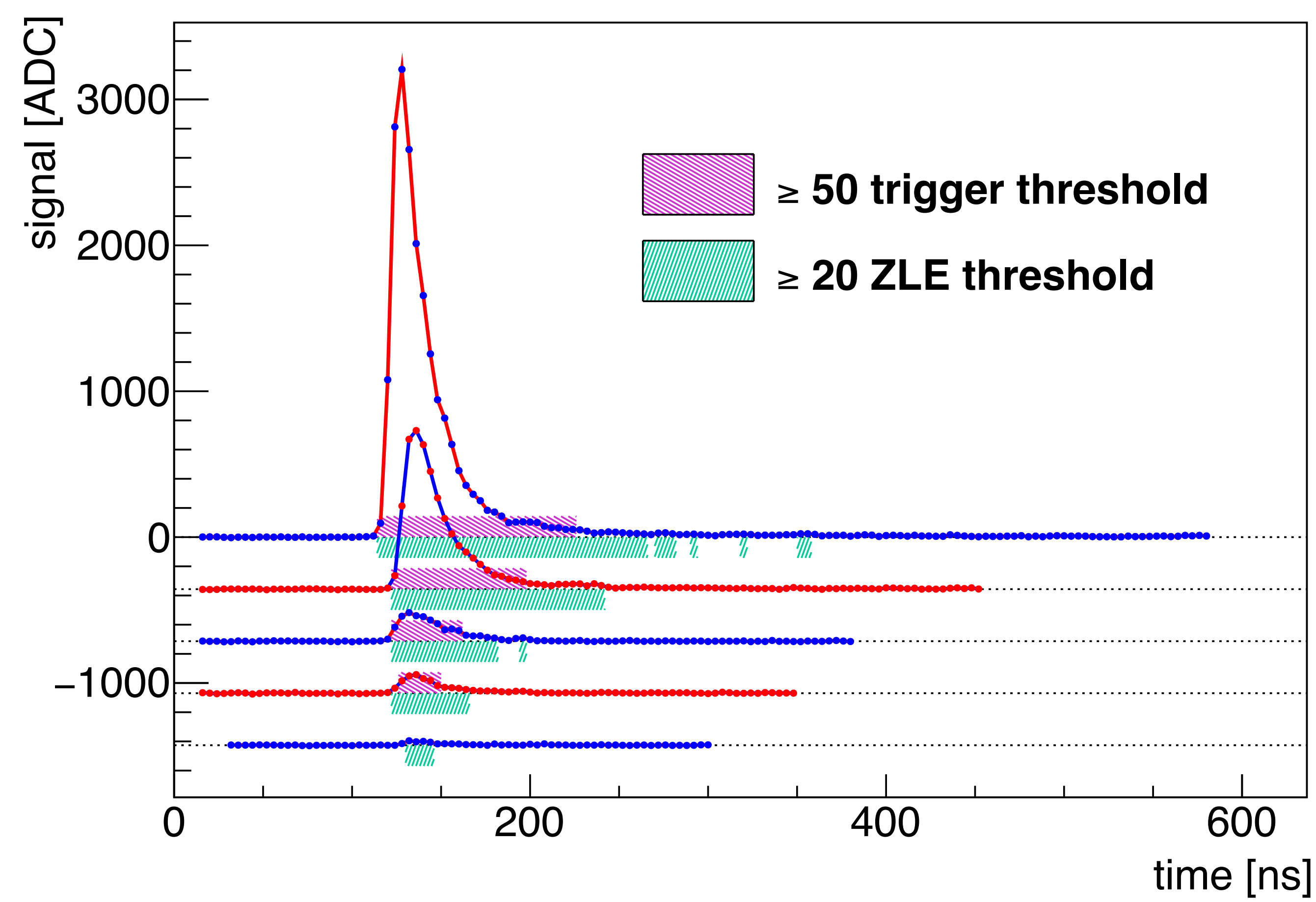



FINAL ROW INSTALLATION
NOVEMBER 17, 2017
YALE WRIGHT LAB

Low-Level Processing Examples

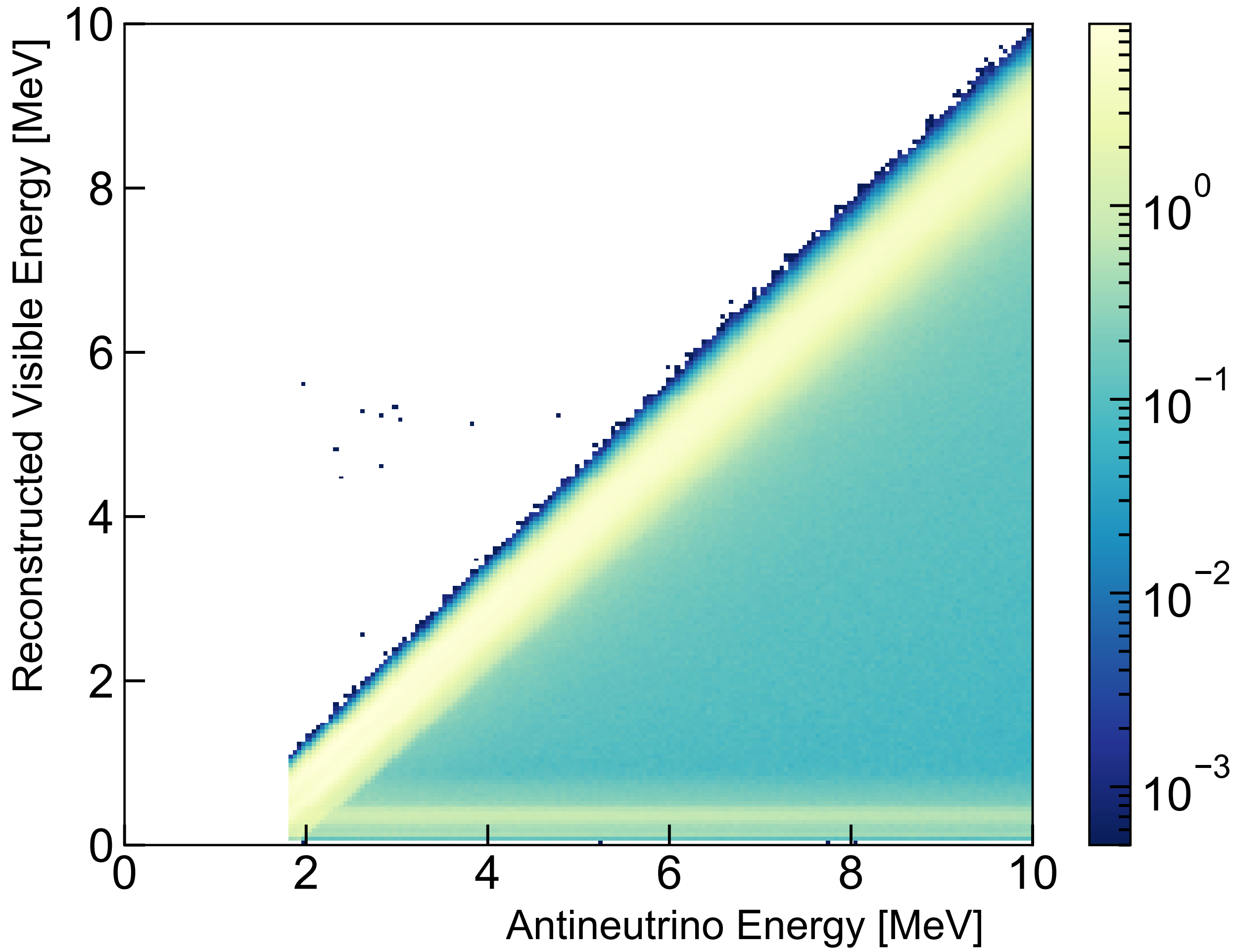
- 50 ADC (~5 PE) trigger threshold: both PMTs on a segment
- 20 ADC (~2PE) zero-suppression threshold
  - Only read out waveform chunks in the vicinity of 20+ ADC sections
- FADC low-level pulse processing quantities:
  baseline, pulse area, PSD peak + tail, timestamps

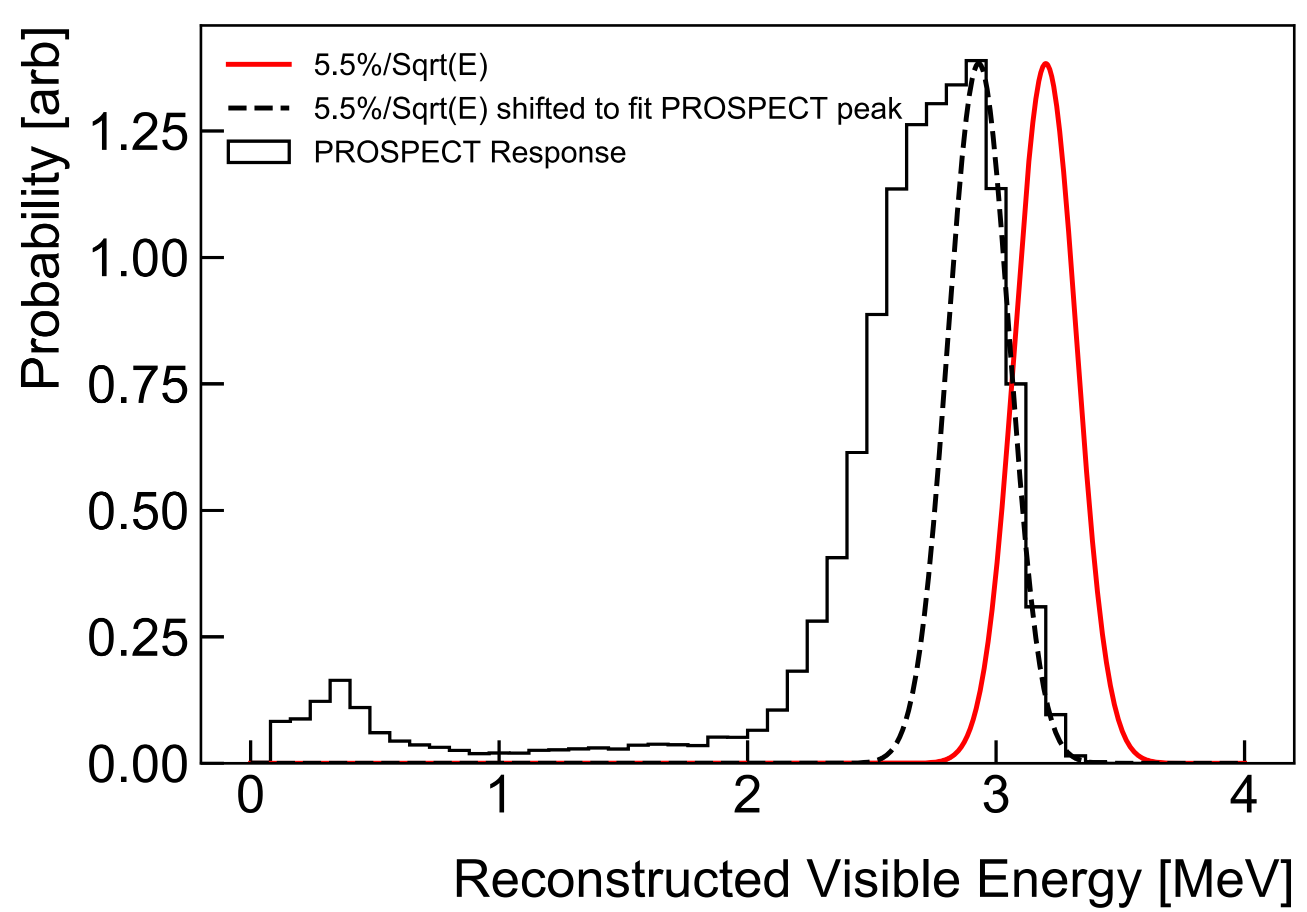




IBD MC: Predicted Energy Response

- Full-detector IBD prompt energy response modeled by PG4 IBD MC
- Substantial off-diagonal contribution from energy leakage into dead/non-fiducial segments, optical grid walls





Non-Fuel Contributions

- Non-negligible neutrinos from activation of Al-28 in core structure, production of He-6 in beryllium reflector
- ~9% contribution at lowest IBD energies
- Effect is stable within 0.1% at cycle beginning and end.

[PROSPECT, PRL 122 (2019)](#)