Energy Scale Calibration in PROSPECT

June 1, 2018

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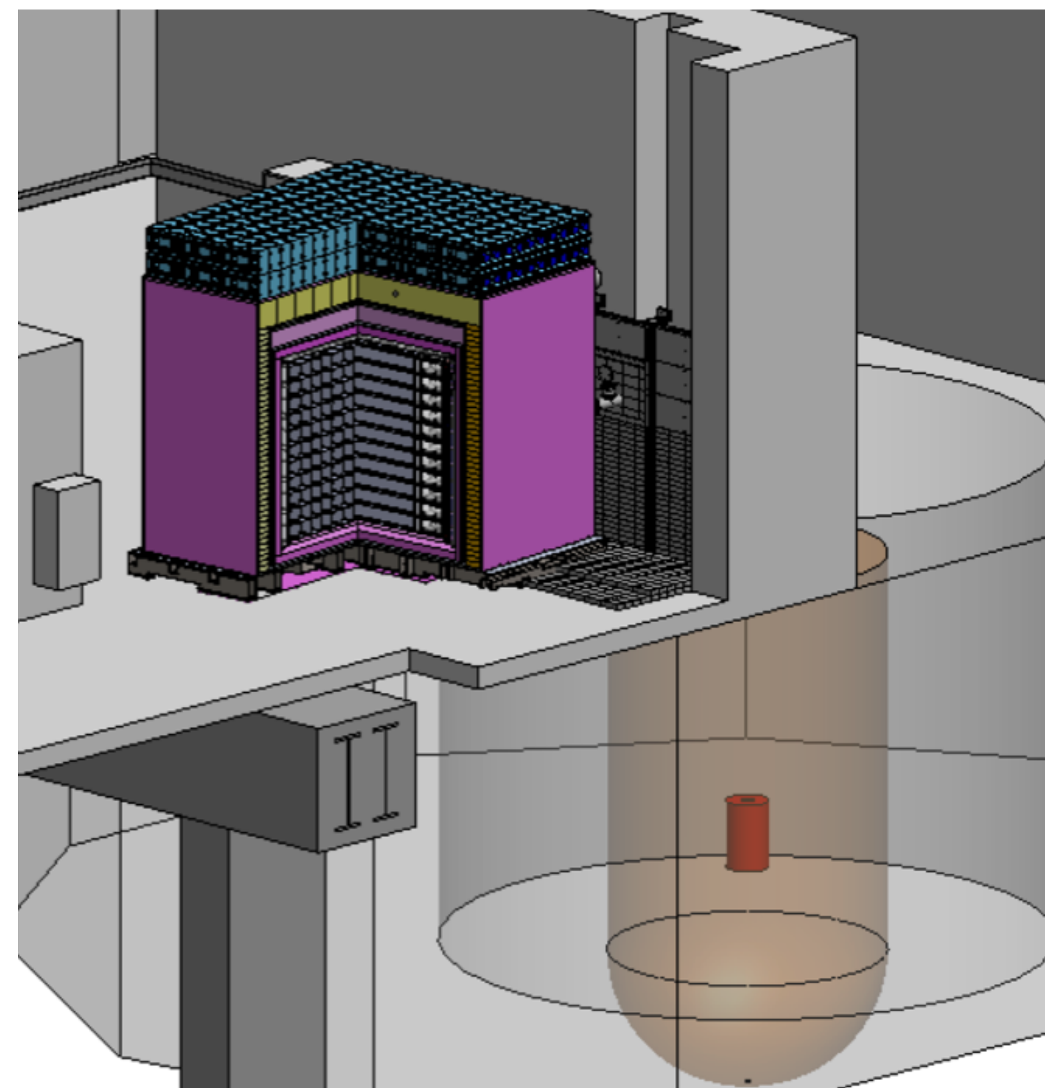
on behalf of the PROSPECT collaboration

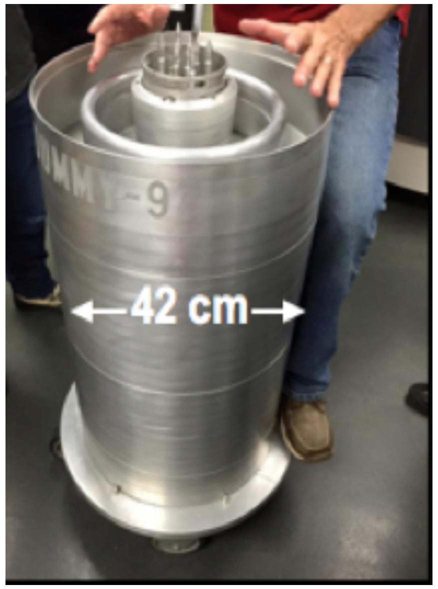
PROSPECT Overview

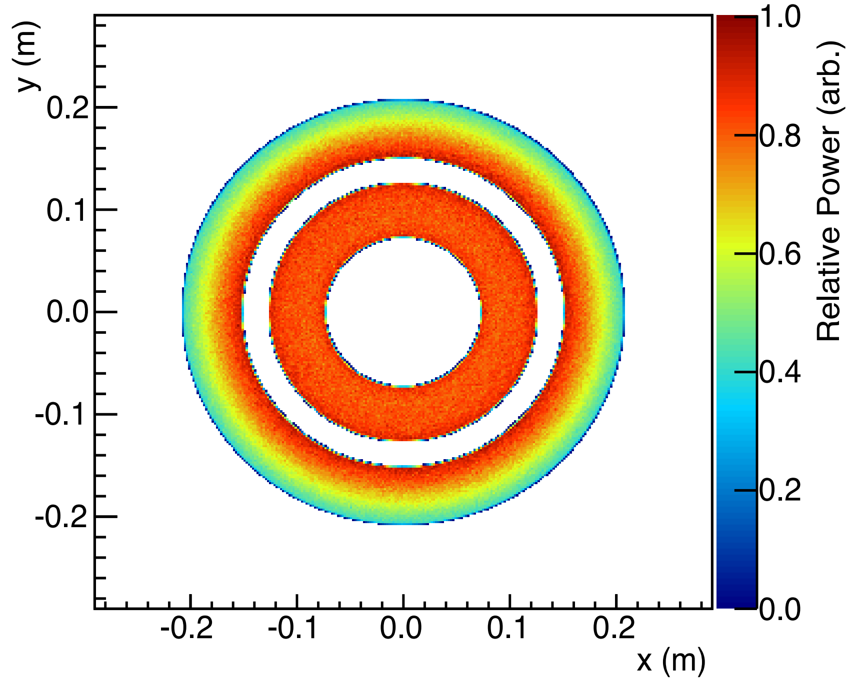
- Short-baseline reactor antineutrino experiment
- Recently installed at High Flux Isotope Reactor (HFIR) at Oak Ridge National Lab (ORNL) in Tennessee, USA
- On-surface: minimal overburden
- Aims:
  - Search for eV-scale sterile oscillations
  - Measure the ^{235}U antineutrino spectrum

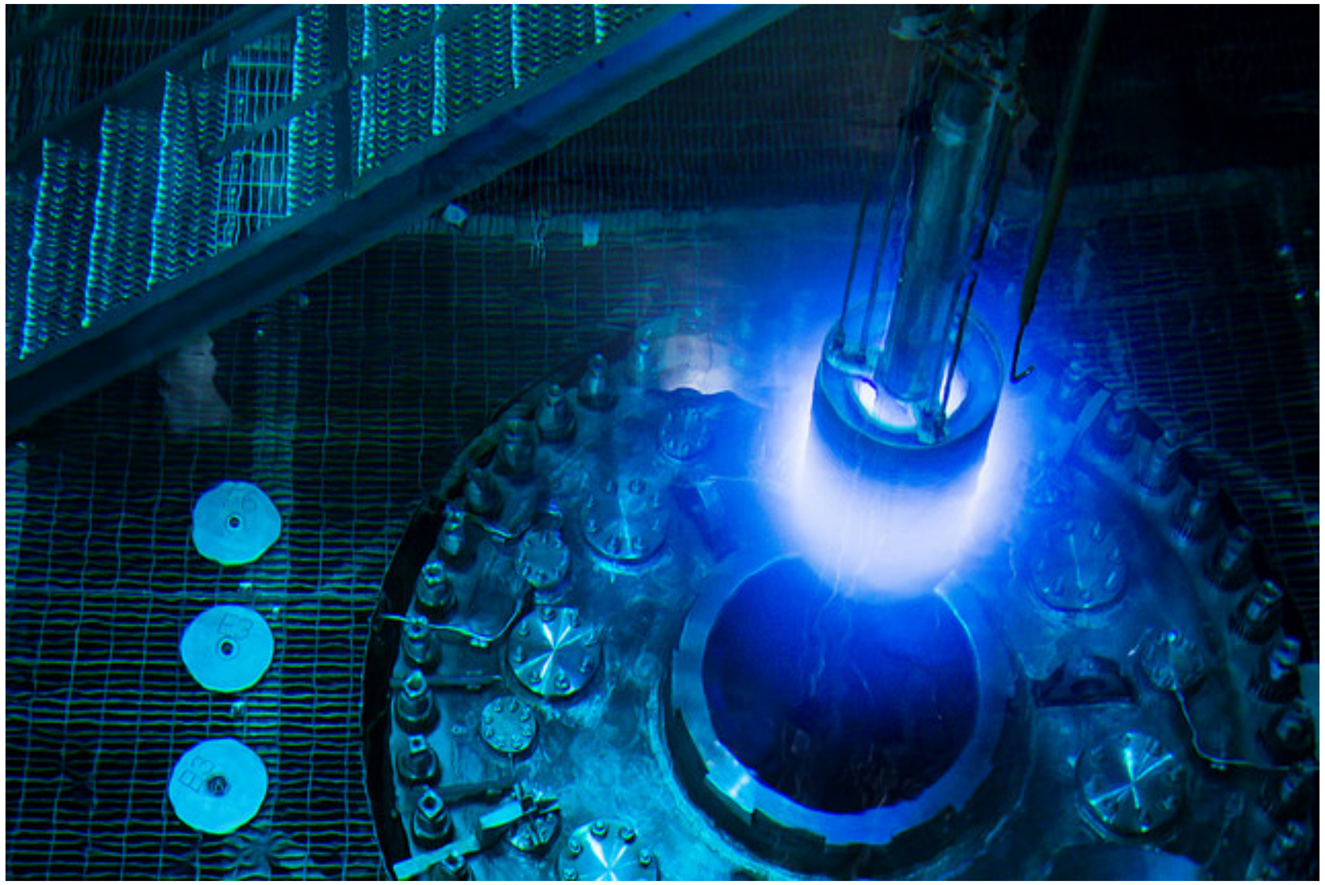


Why HFIR?

- 85 MW HEU reactor: >99% ^{235}U fissions
- Compact core: 50cm tall, 42cm wide
- Position available near the core (7 - 12 m)
- Short reactor cycles (~25d)
- >50% reactor off-time for background measurements
- As a user facility, detailed core model is available

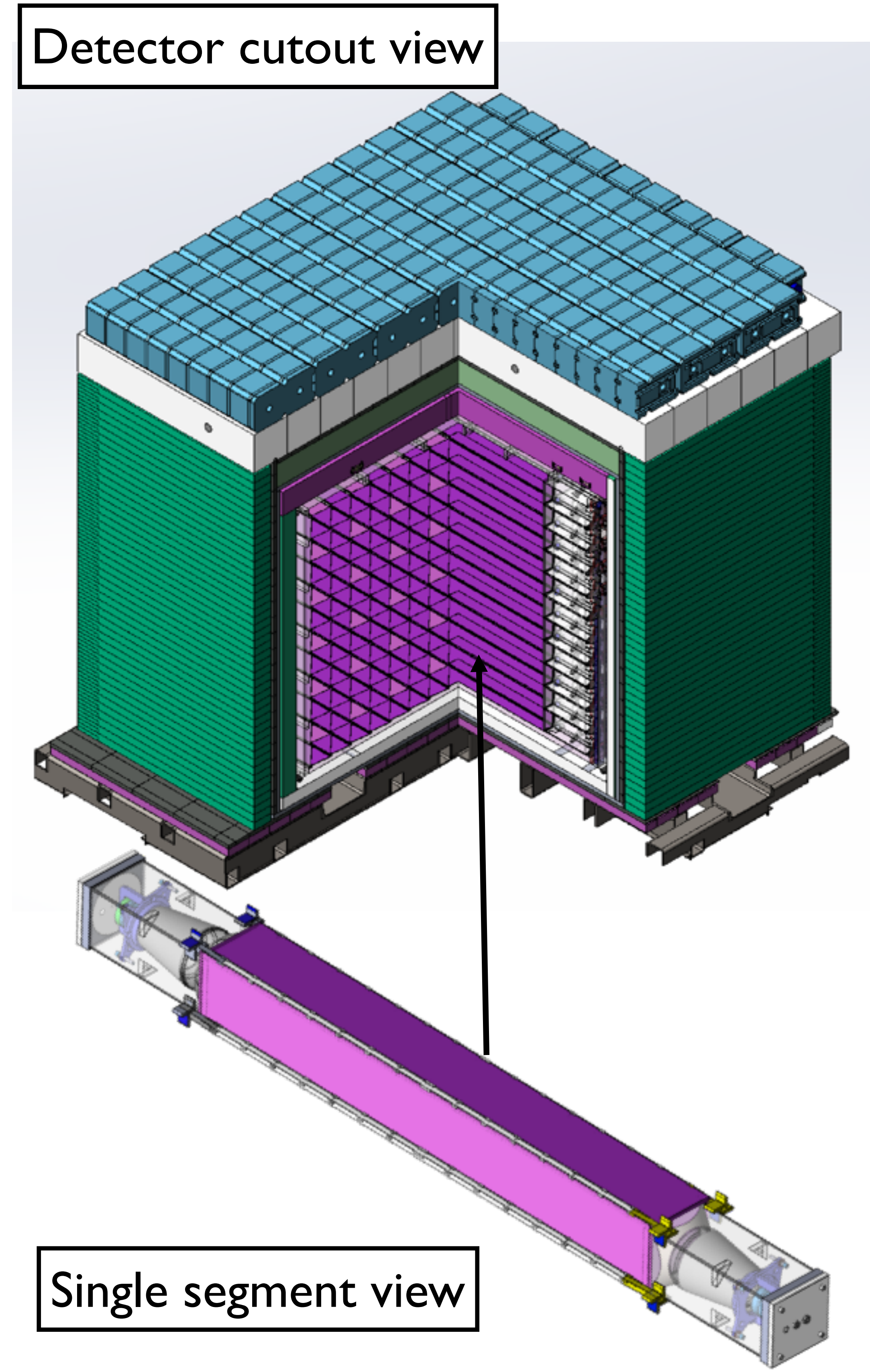






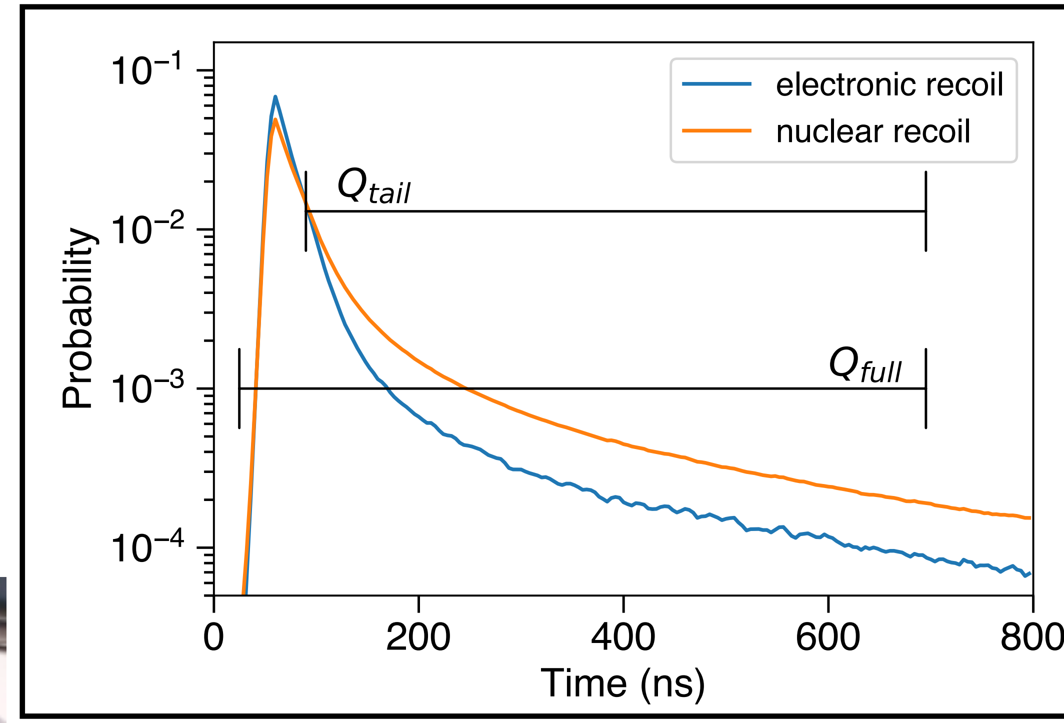
Experimental Design

- Segmented design
  - Single 4-ton scintillator volume
  - Optical subdivided into 154 (11x14) isolated segments
  - Segment read out by PMTs on each end
- Target spans ~2m of baseline
- Pulse-shape discriminating (PSD) scintillator, 0.1% ^{6}Li by weight
  - non-flammable, non-toxic
  - doped with trace ^{227}Ac for calibration
- Full PMT waveform readout
- Entire assembly built on moveable air caster platform

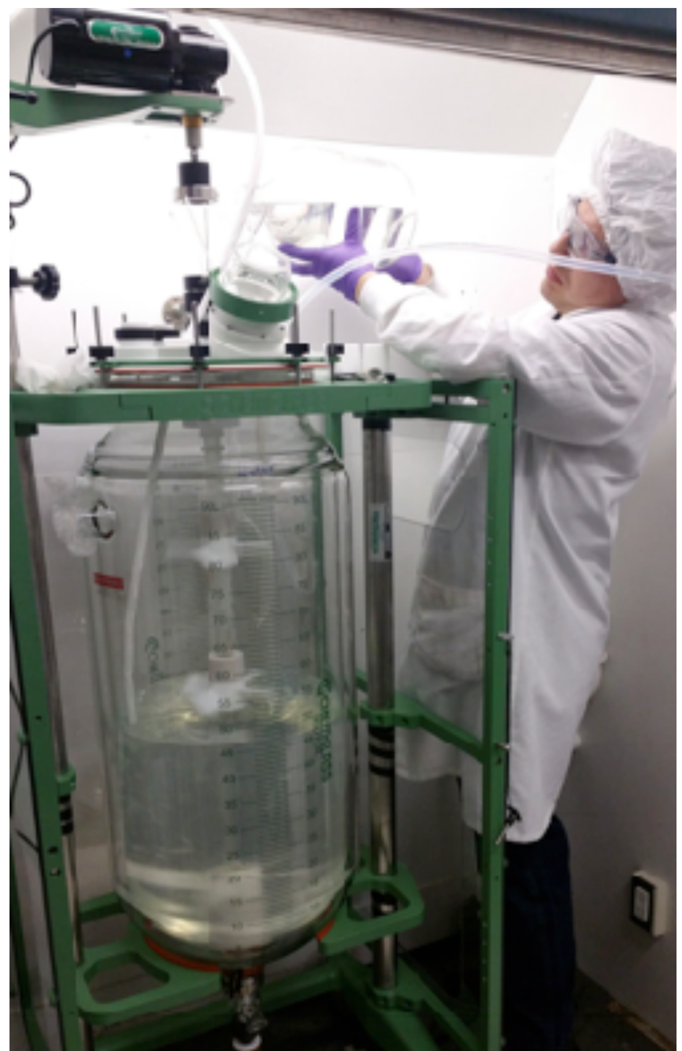


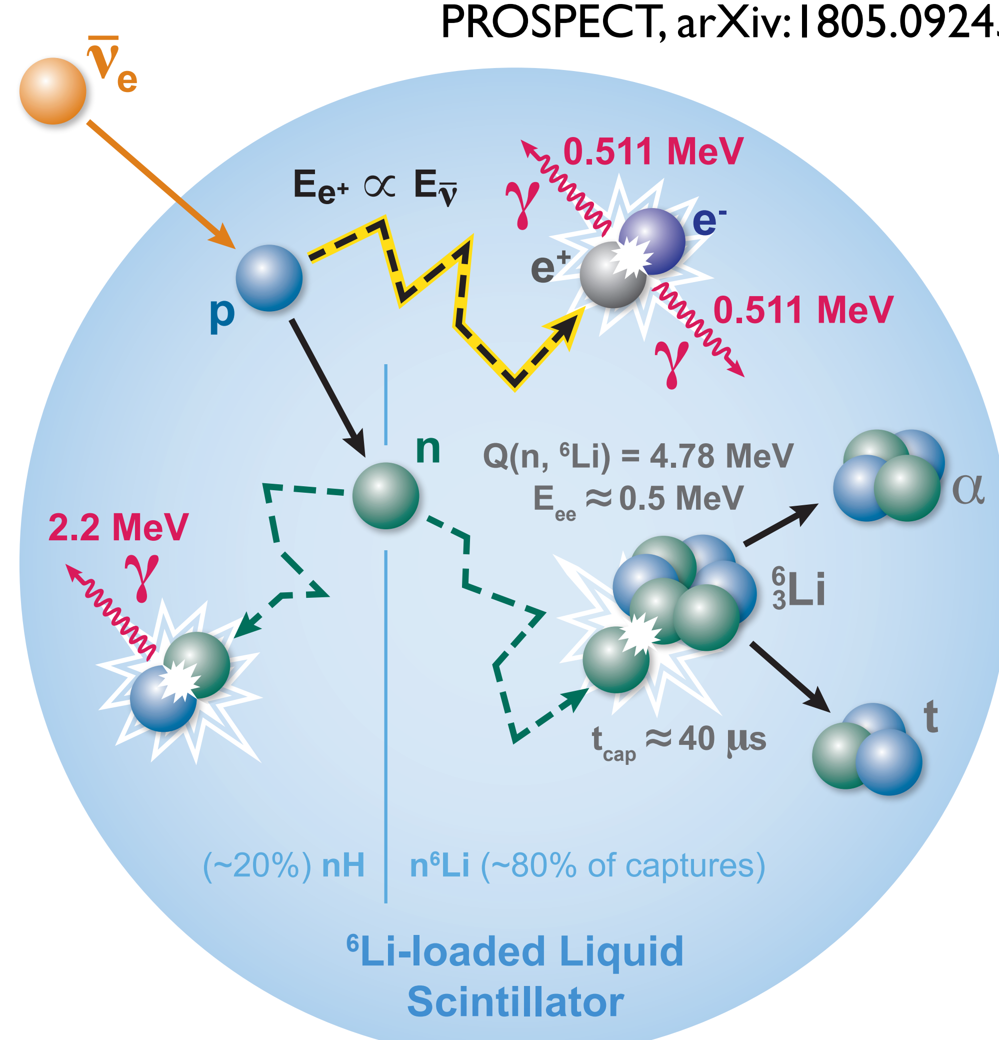
AD Tour: Li-Doped Scintillator

- **Li-doped LS provides unique signature for antineutrino detection**
  - Inverse beta decay (IBD) on p in scintillator
  - IBD neutrons capture on ^{6}Li
  - Specific PSD signature from correlated prompt/delayed signals
- LiLS developed by PROSPECT
  - Based on Eljen EJ-309
  - ^{6}Li dissolved in water, surfactant enables stable water/LS mix
  - QA/QC, compatibility tests performed at many PROSPECT institutions



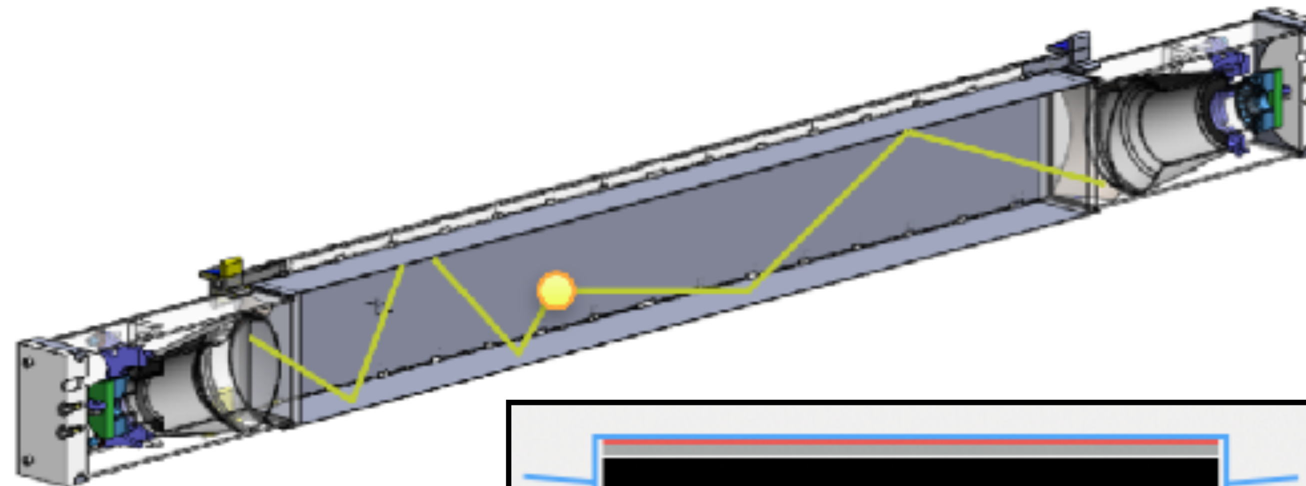
PROSPECT, arXiv:1805.09245

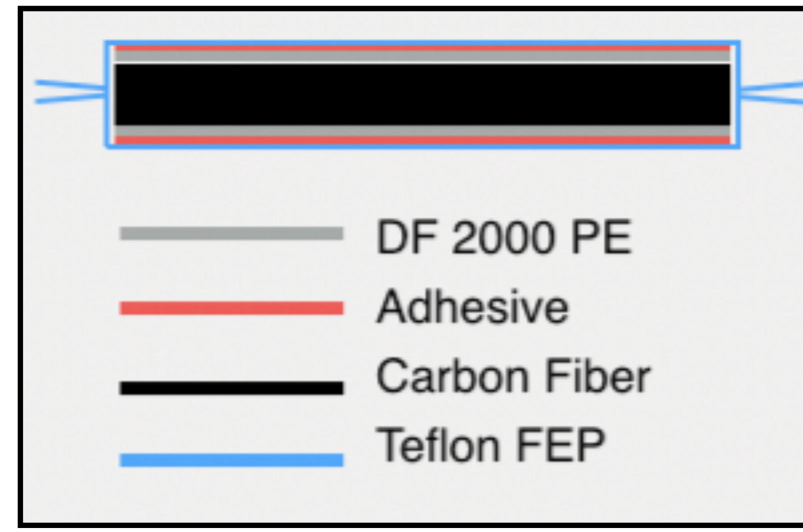

AD Scintillator Production:
Production batch size



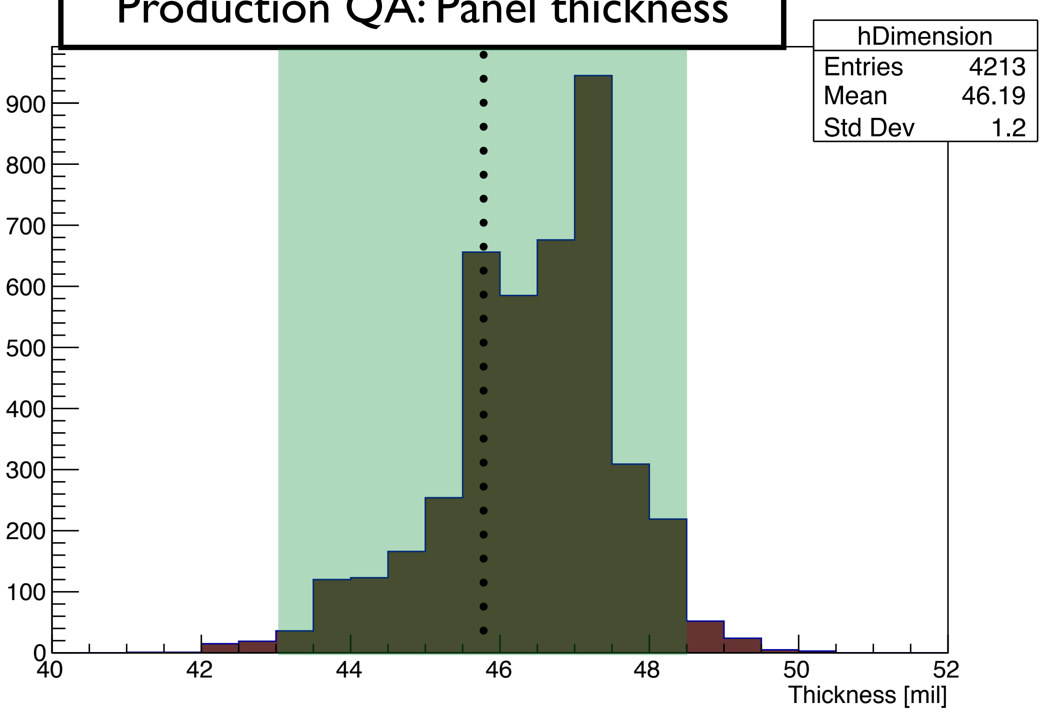
AD Tour: Target Segmentation System

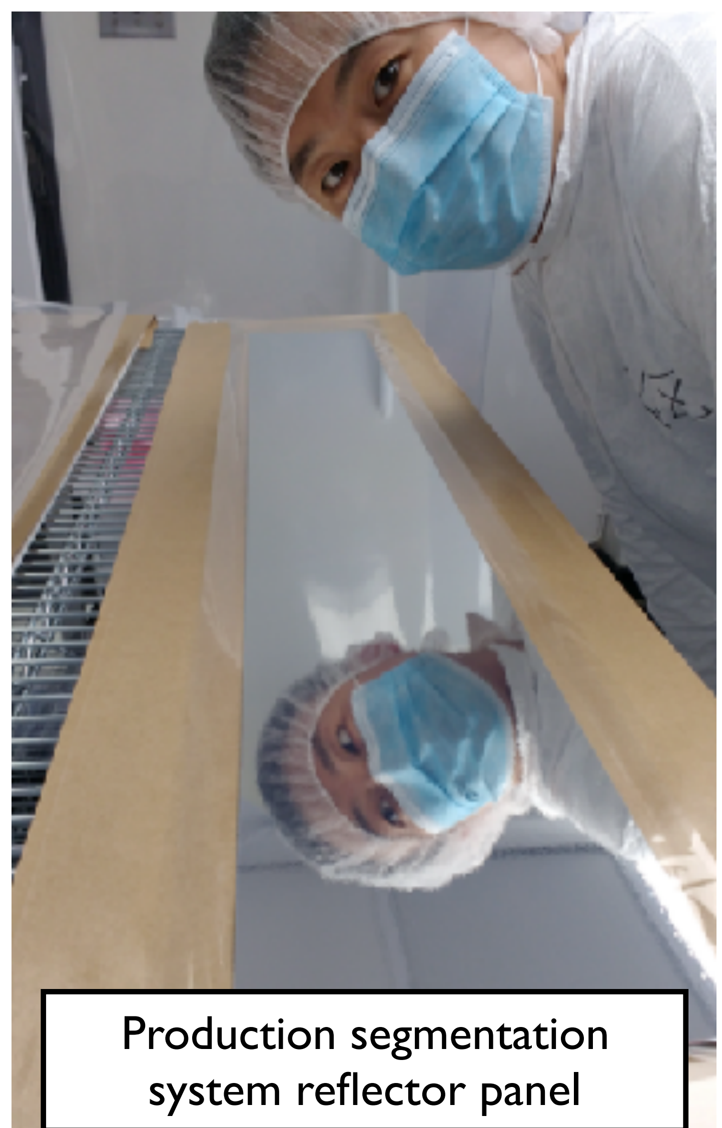
- Optical panels direct light to PMTs at either cell end
  - Total internal reflection from teflon casing
  - Specular reflection from 3M DF2000M foils
  - Fabrication completed at IIT in mid-2017
  - QA/QC done in parallel





Production QA: Panel thickness



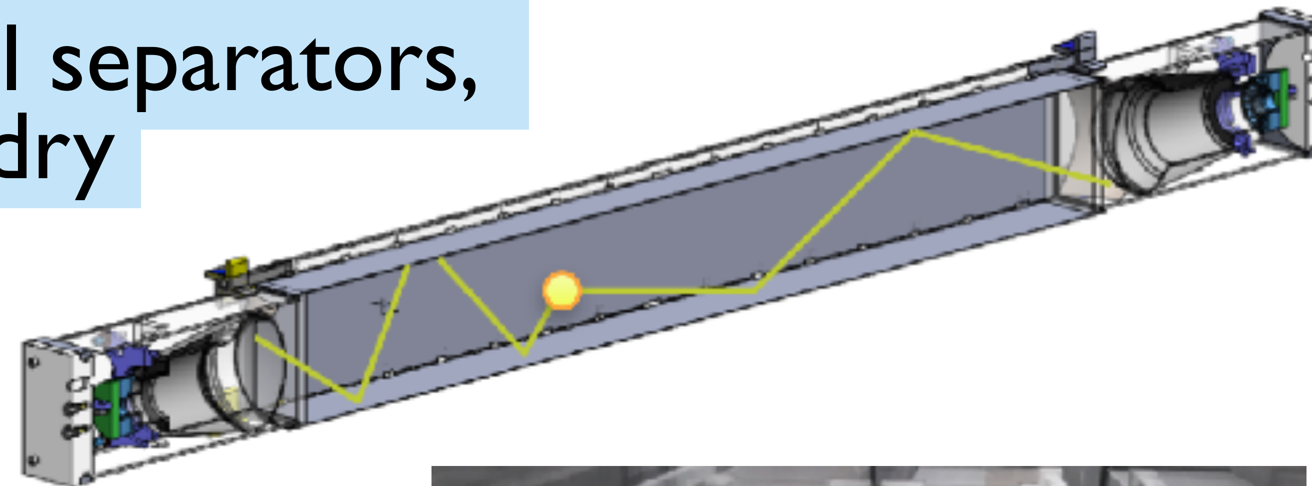


Production segmentation system reflector panel

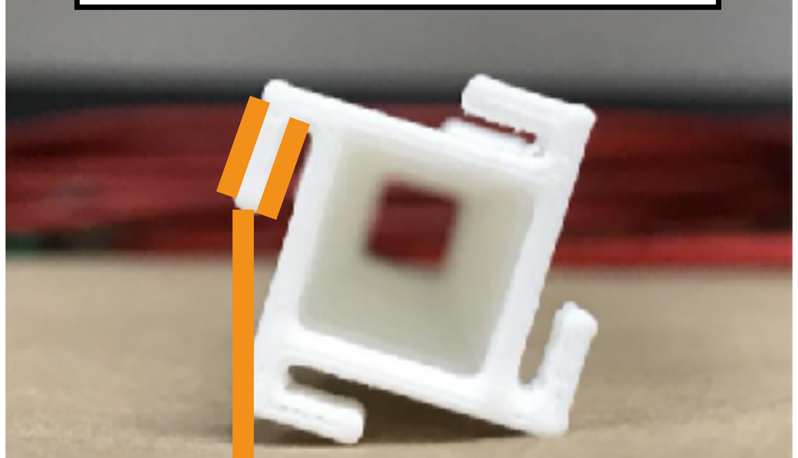
Optical Separator Fabrication

AD Tour: Support Rod Components

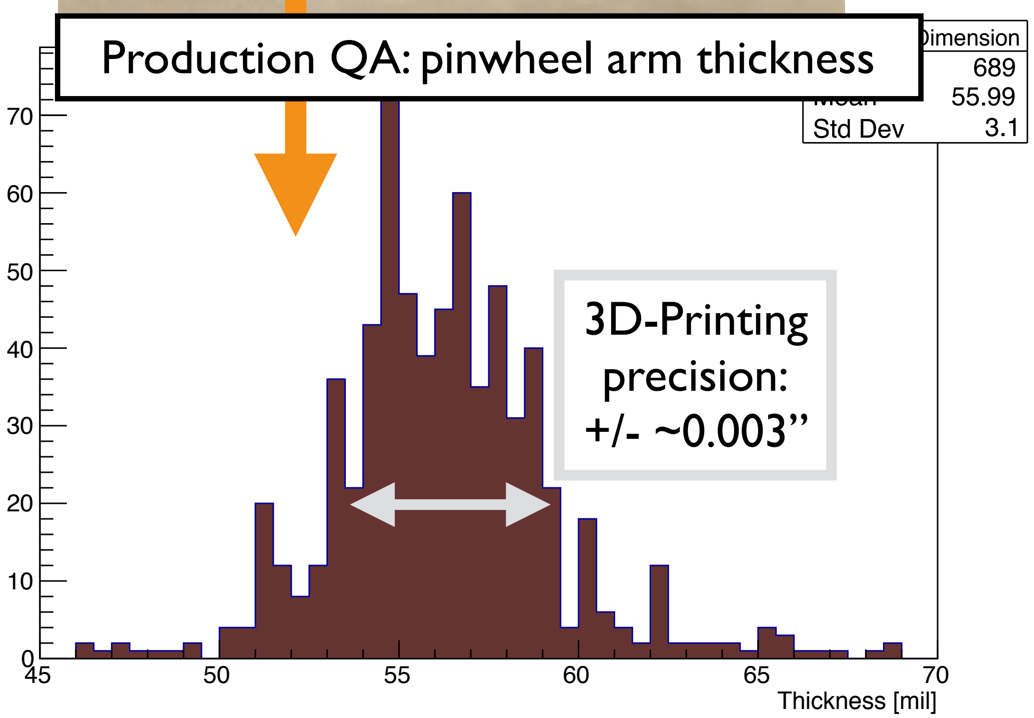
- Pinwheel rods support optical separators, PMT housings while defining dry calibration axes
  - Mass-produced via 3D-printing of ABS plastic extensive QA



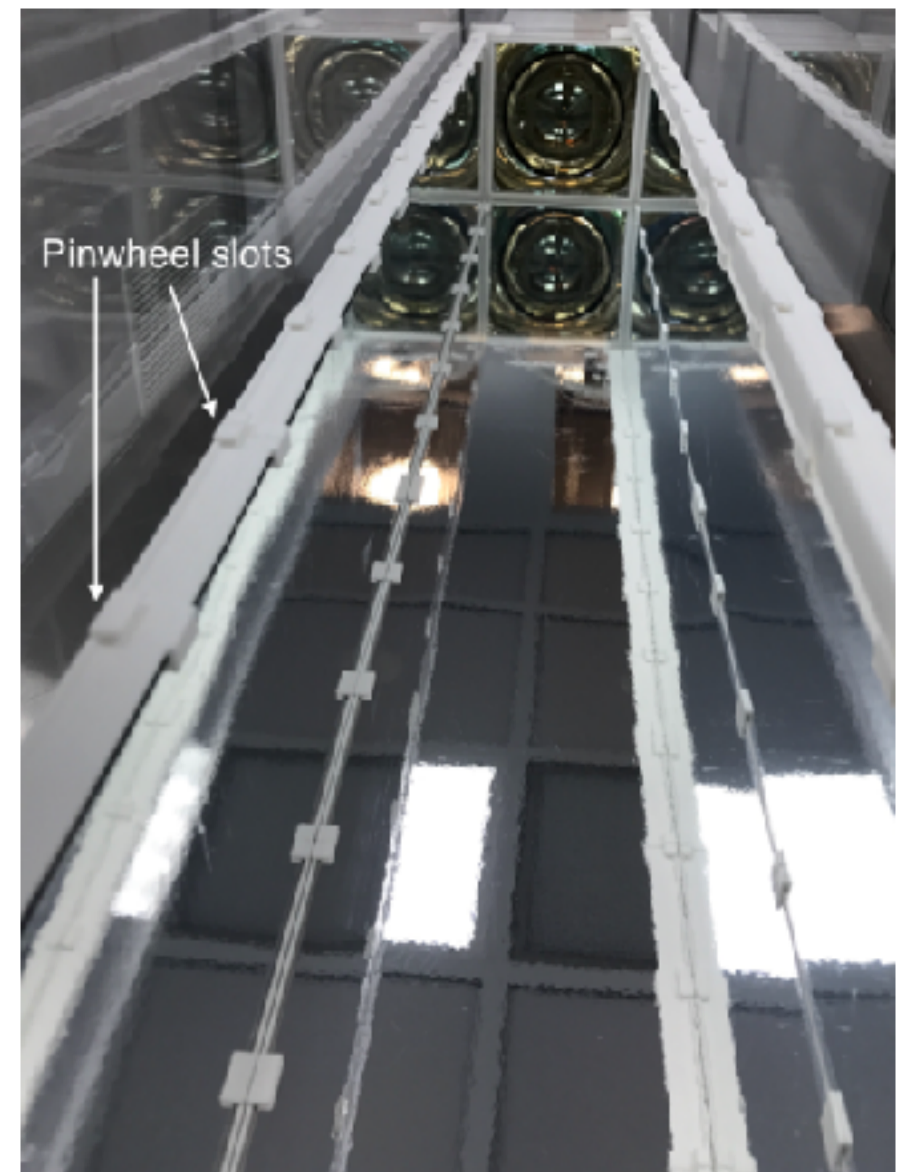
‘Standard’ pinwheel rod



Production QA: pinwheel arm thickness

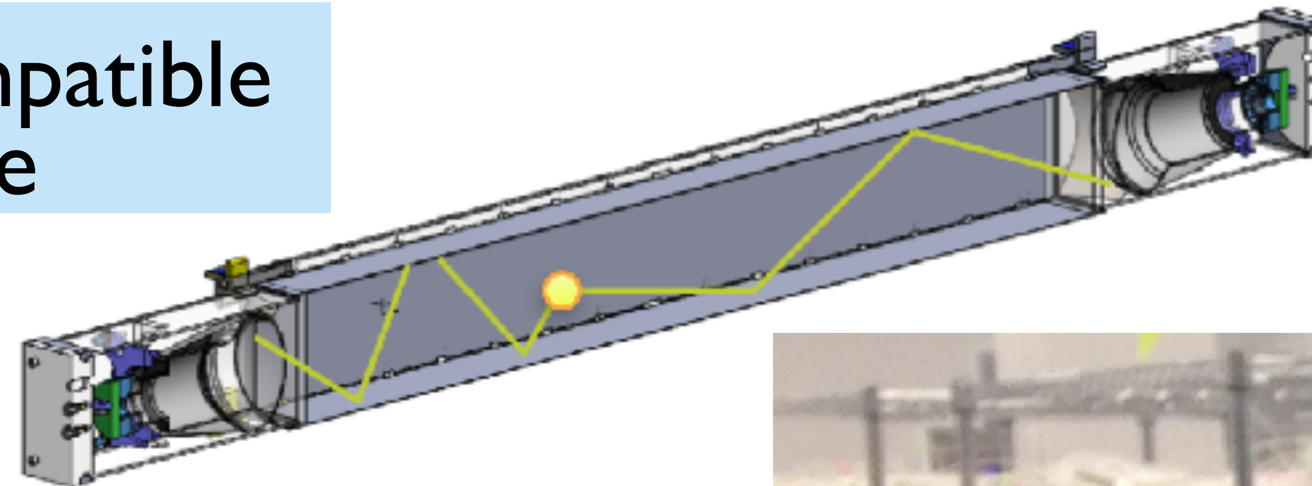


‘Support’ pinwheel rod

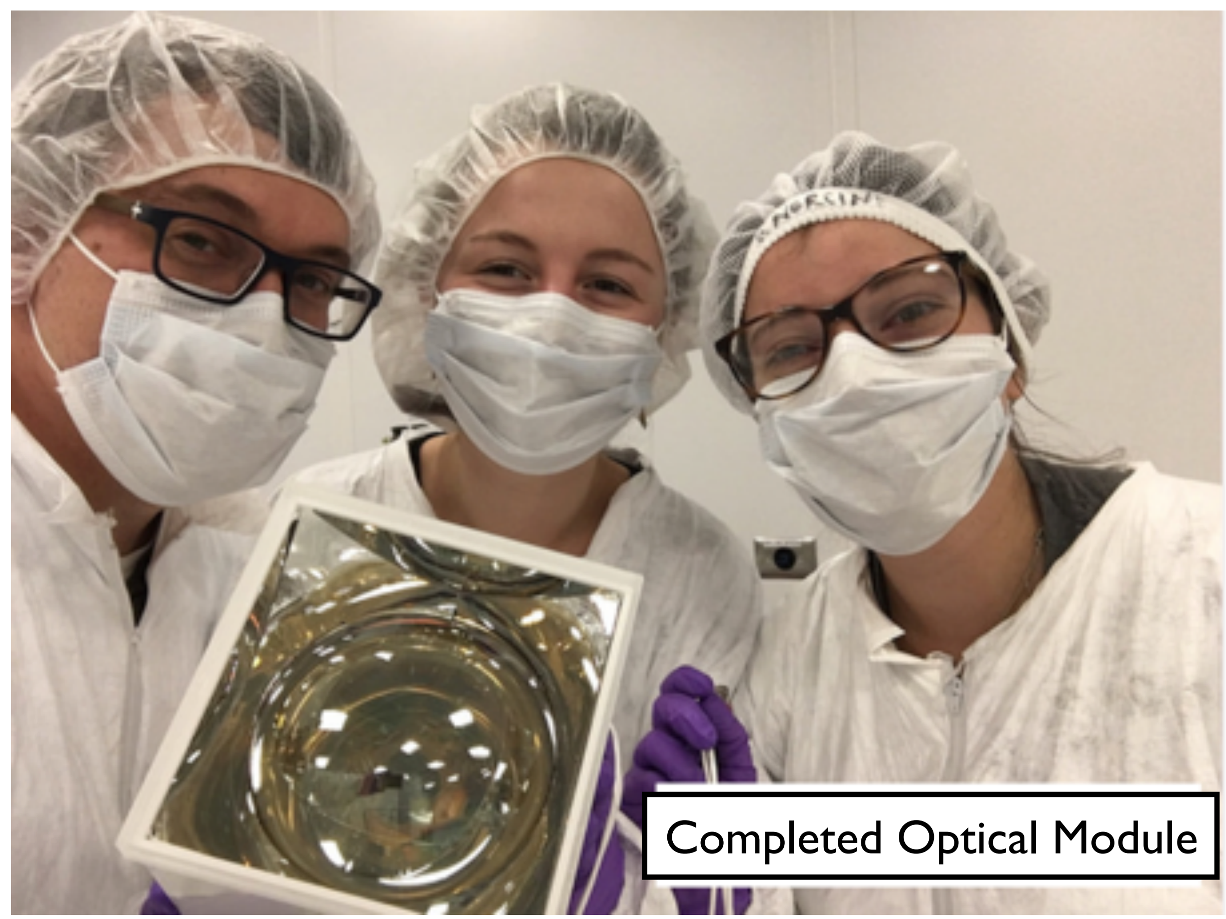


AD Tour: PMT Housings

- Housings separate LiLS-incompatible PMTs from scintillator, provide standard building blocks for assembly of AD target
- Intensive QA procedures
  - Leak checking, PMT testing, and dimensional checks



PMT Burn-in and Testing

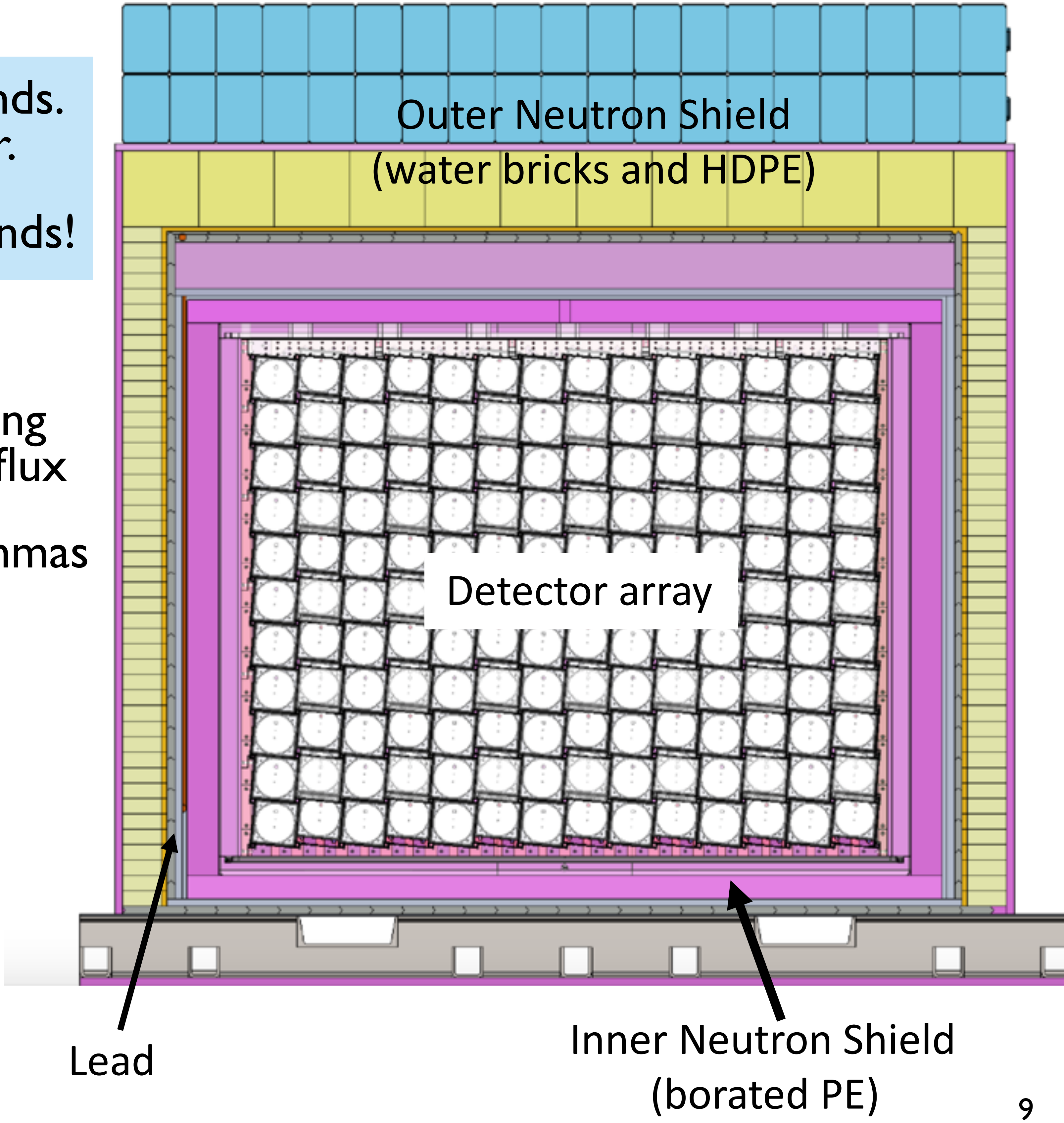


Completed Optical Module

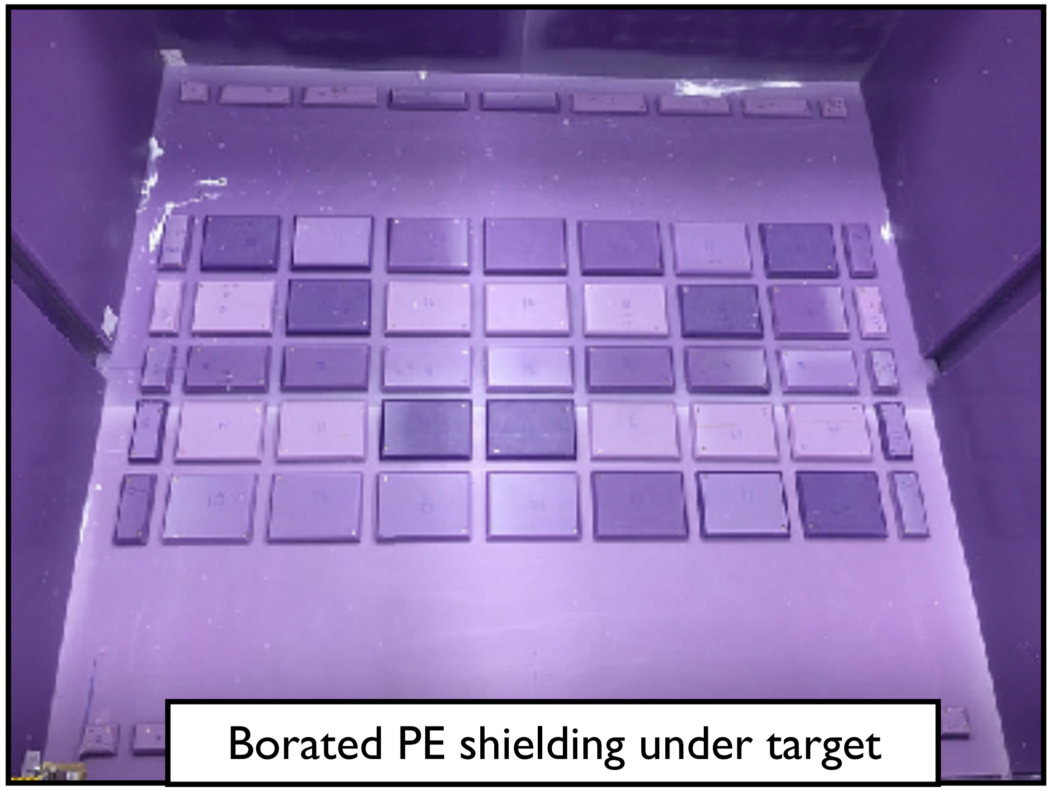
Completed Models Prior to Assembly

AD Tour: Detector Shielding

- Considerations
  - At surface: cosmic backgrounds. cosmic neutrons in particular.
  - At reactor: gamma backgrounds!
- Shielding design
  - Outside: hydrogenous shielding for cosmic, reactor neutron flux
  - Middle: lead for shielding gammas
  - Inner: hydrogenous borated material to shield neutron interactions in lead
  - Can also use outer layer of cells to fiducialize



AD Tour: Detector Shielding



Borated PE shielding under target

Target package with partial lead shielding

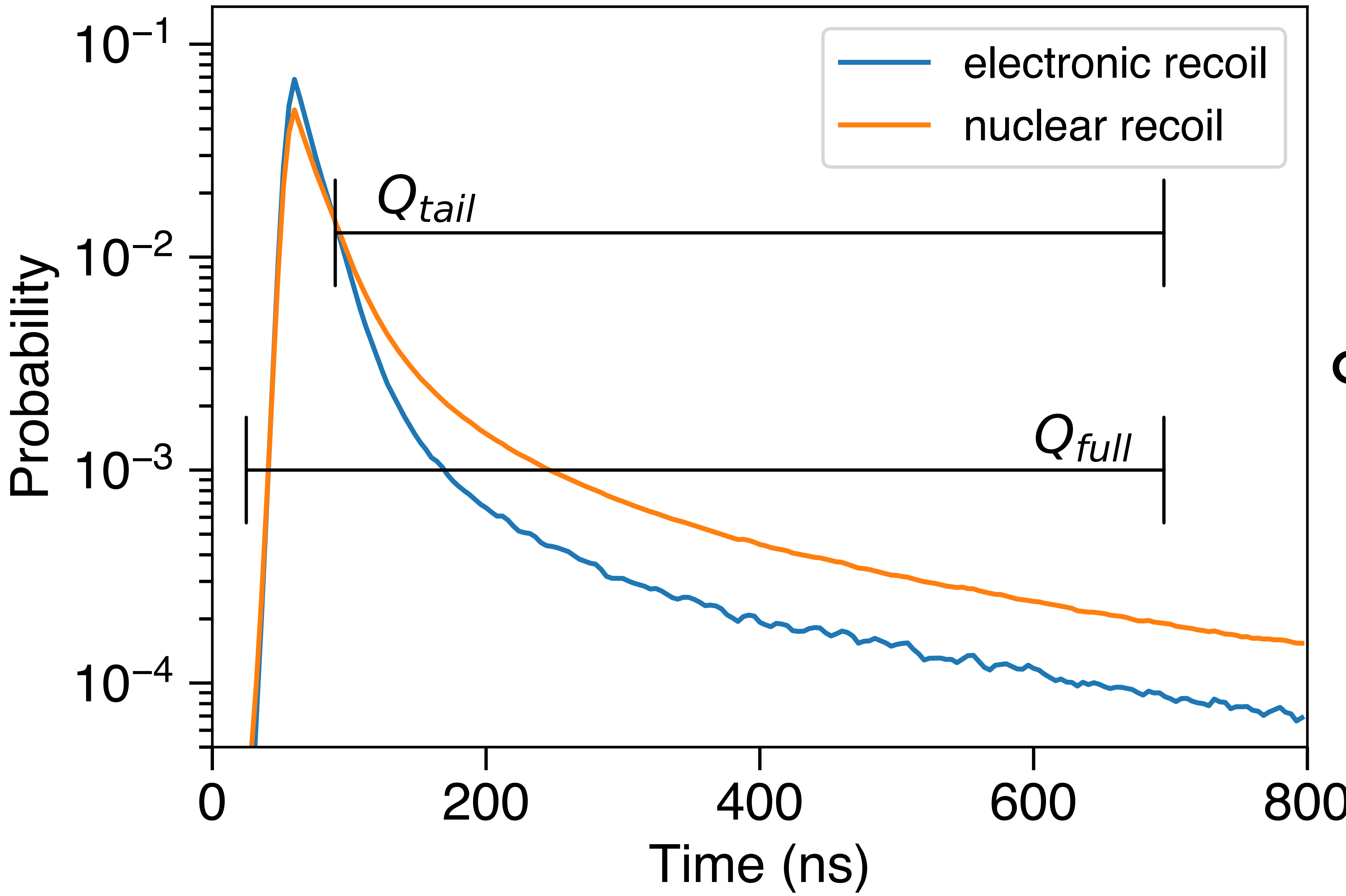
Outer PE layer (in purple)

Same, with fully outer shielding package

AD Tour: Readout

- CAEN 14-bit, 250 MHz fast waveform digitizers
- Zero-suppressed triggering: read out ALL channels above X ADC when ANY segment's channels are above Y ADC.
- 148 total samples per channel readout: ~0.6 us window

PROSPECT, arXiv:1805.09245



Imagine reading out the first 148 samples of these waveforms…

Clearly well-suited for PSD scintillator!

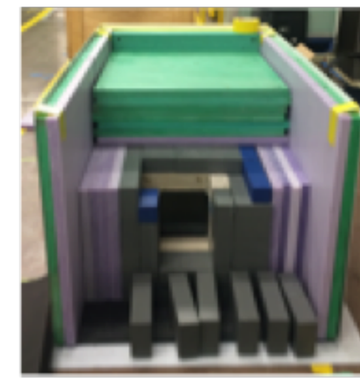
Development Timeline

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
NIM A 806 401 (2016)

12.5 length
1.7 liters
^{6}LiLS



multi-layer shielding

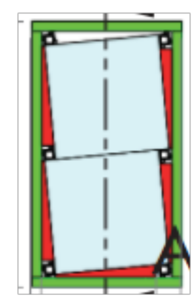
PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015
JINST 10 P11004 (2015)

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

PROSPECT-50
Baseline design prototype
Spring 2016

arXiv:1805.09245

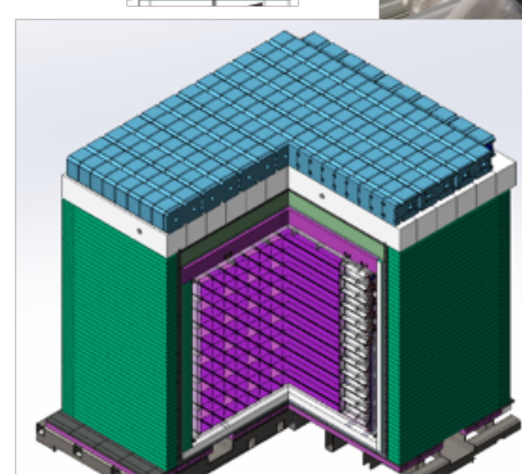
1x2 segments
1.2m length
50 liters
^{6}LiLS

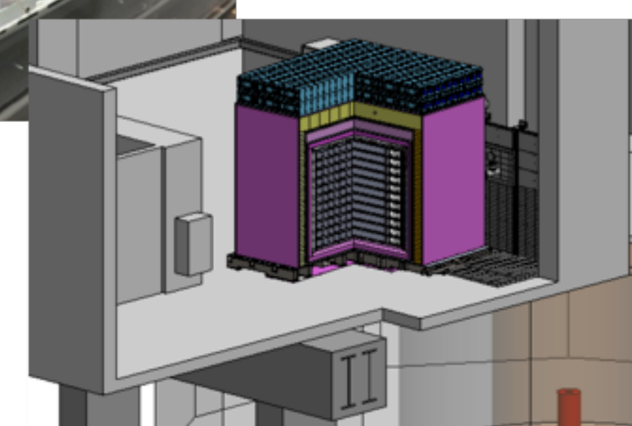


local reactor shielding

PROSPECT AD
2017

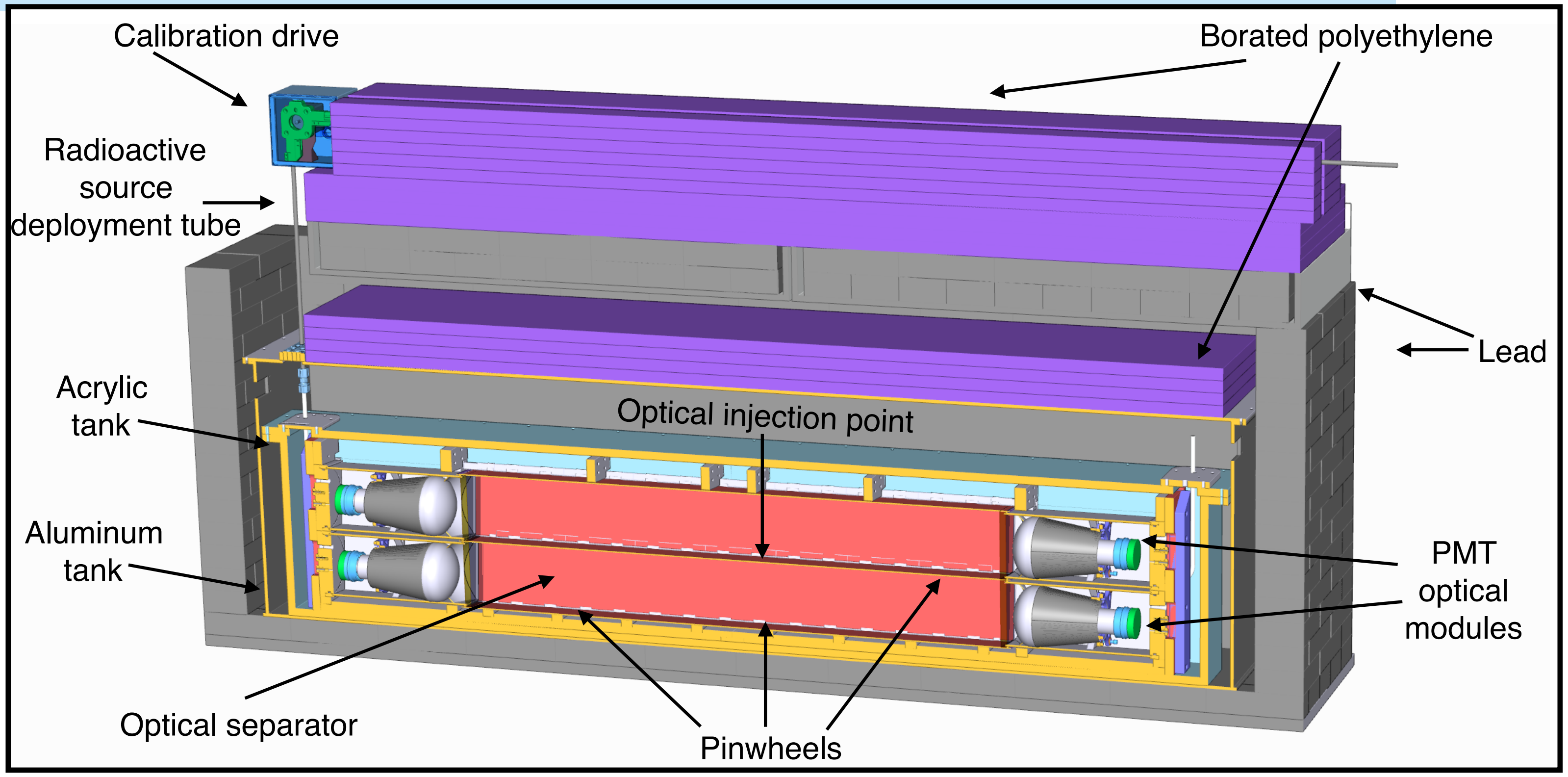
11x14 segments
1.2m length
~4 tons
^{6}LiLS

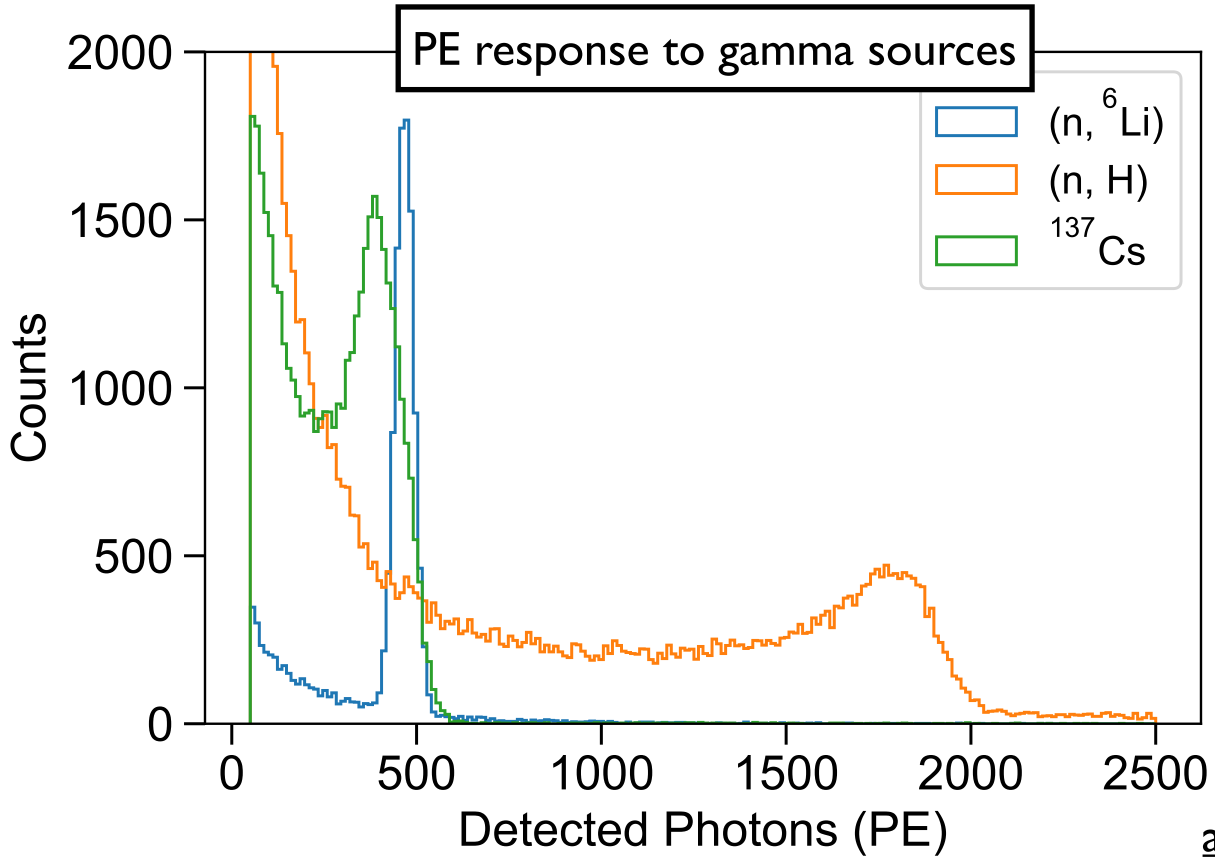


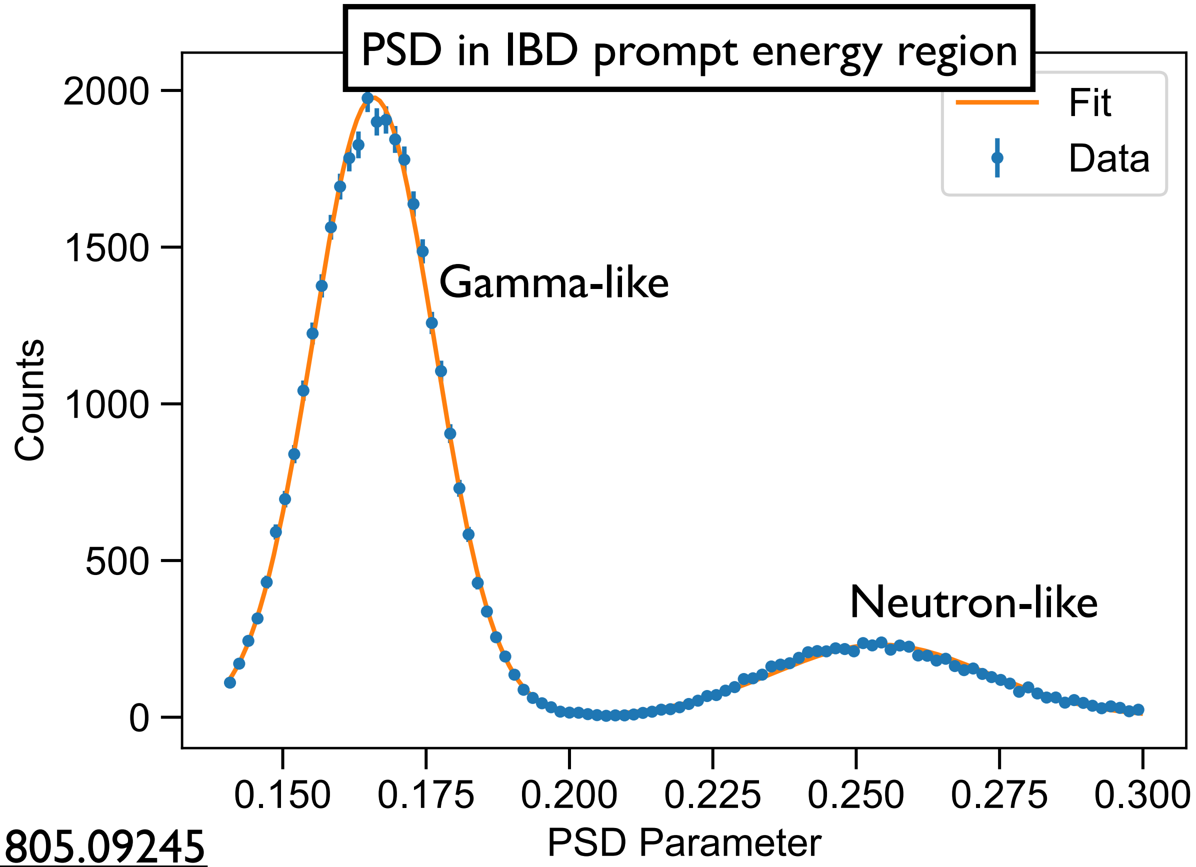


Recent Development Example: P50

- Demonstrated detector performance in full 2-cell prototype
  - >800 PE/MeV: ~4%/$\sqrt{E}$ photo-statistics resolution
  - 85cm cell attenuation length
  - Excellent PSD (FOM=1.5)
  - Can reconstruct positions along a cell length using time and charge information







arXiv:1805.09245

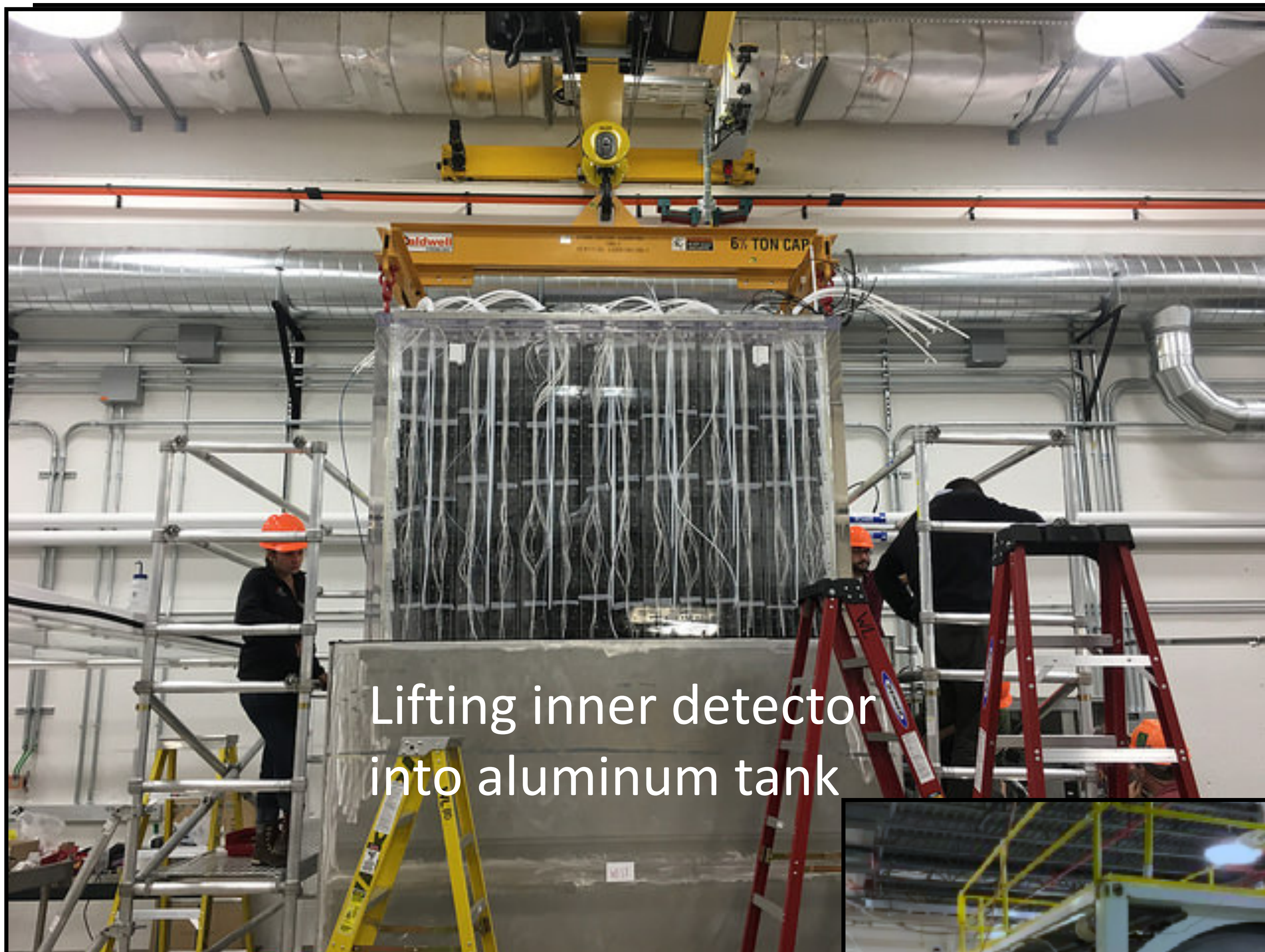
Detector Assembly

Detector Assembly

Detector Assembly

https://prospect.yale.edu/media

Lifting, Transport, Filling



Lifting inner detector into aluminum tank

Loading detector on truck for trip to HFIR

Mixing tank and scintillator barrels at Oak Ridge

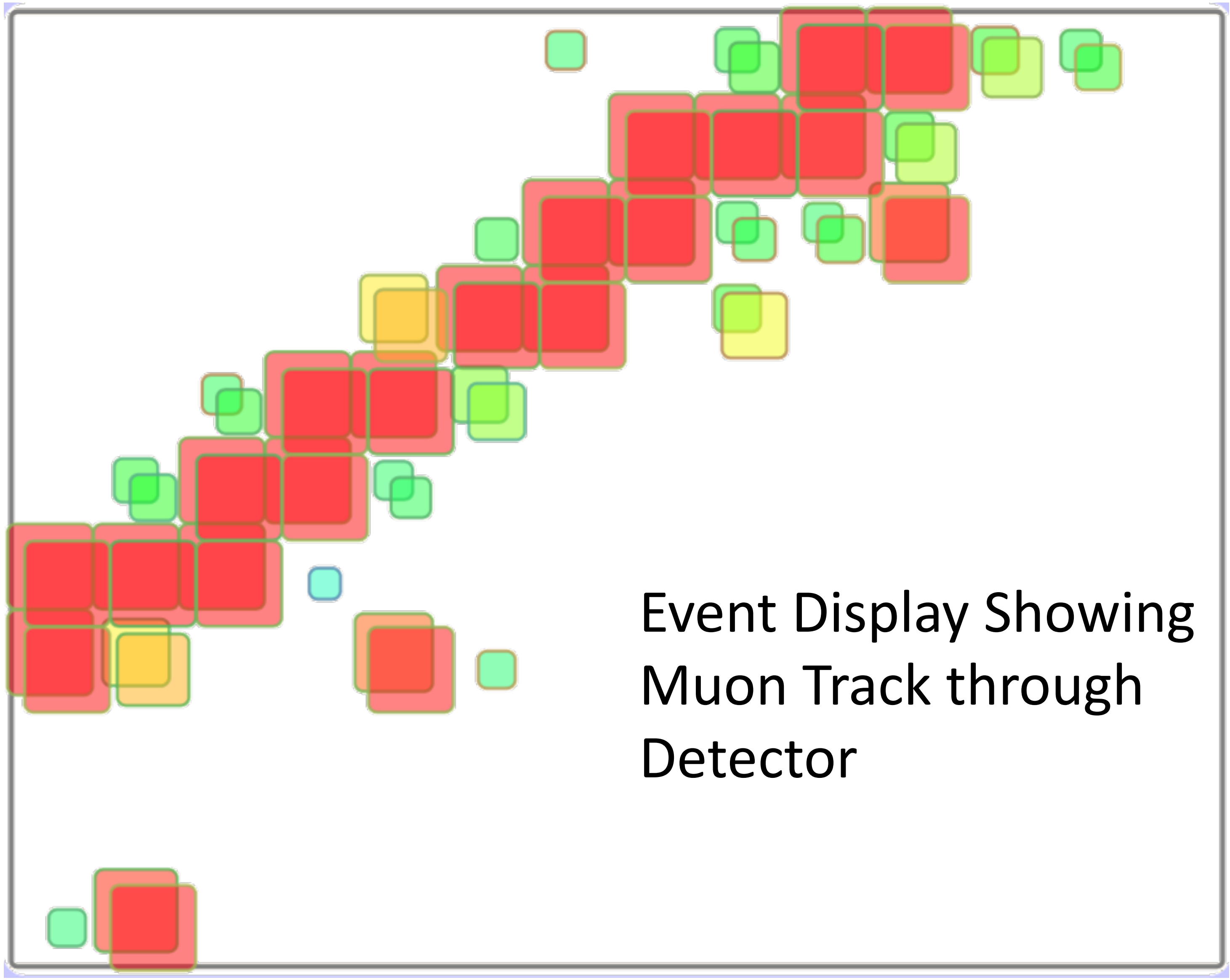
Installation at HFIR

Fully installed AD

Fully installed AD Racks

PROSPECT Is Now Operational

- Detector installed and filled with scintillator in mid-February
- Followed by period of commissioning
- Background data and partial commissioning during March-April
- We are now in neutrino data-taking mode.



https://news.yale.edu/2018/05/18/prospecting-antineutrinos

SBL Reactor Experiment Requirements

- Primary requirements to meet PROSPECT physics goals:
- Spectrum measurement:
  - HEU reactor: enables comparison to existing LEU measurements
  - Energy resolution: enables elucidation of features in specific energy ranges
  - Well-understood absolute response: ultimate limiter of measurement precision
- Sterile neutrino search:
  - Multiple baselines: required for a sterile search independent of the exact underlying spectrum shape.
  - Well-understood relative response: enables relation of any baseline-to-baseline signal variations directly to short-baseline oscillations
- Meet requirements while also rejecting copious backgrounds

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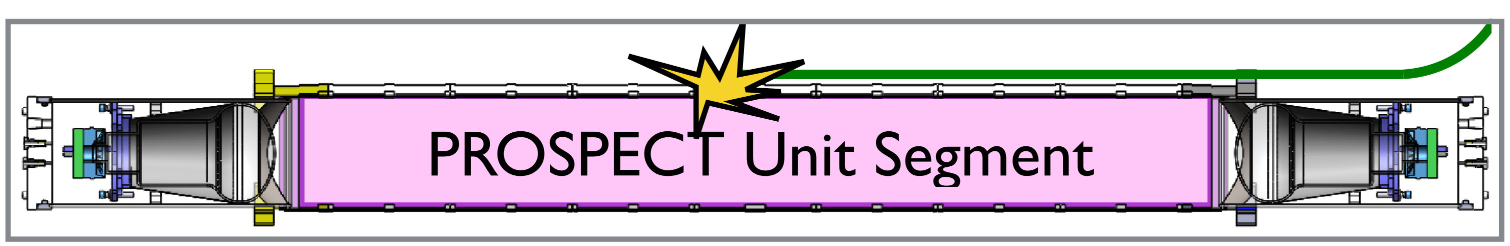
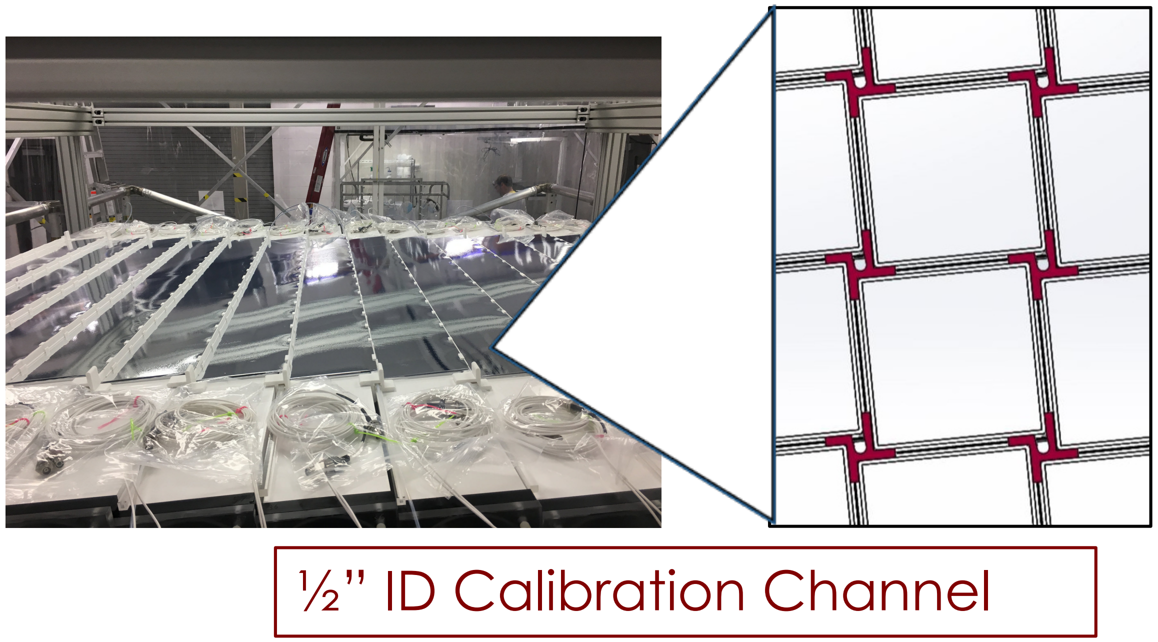
Calibration Principles

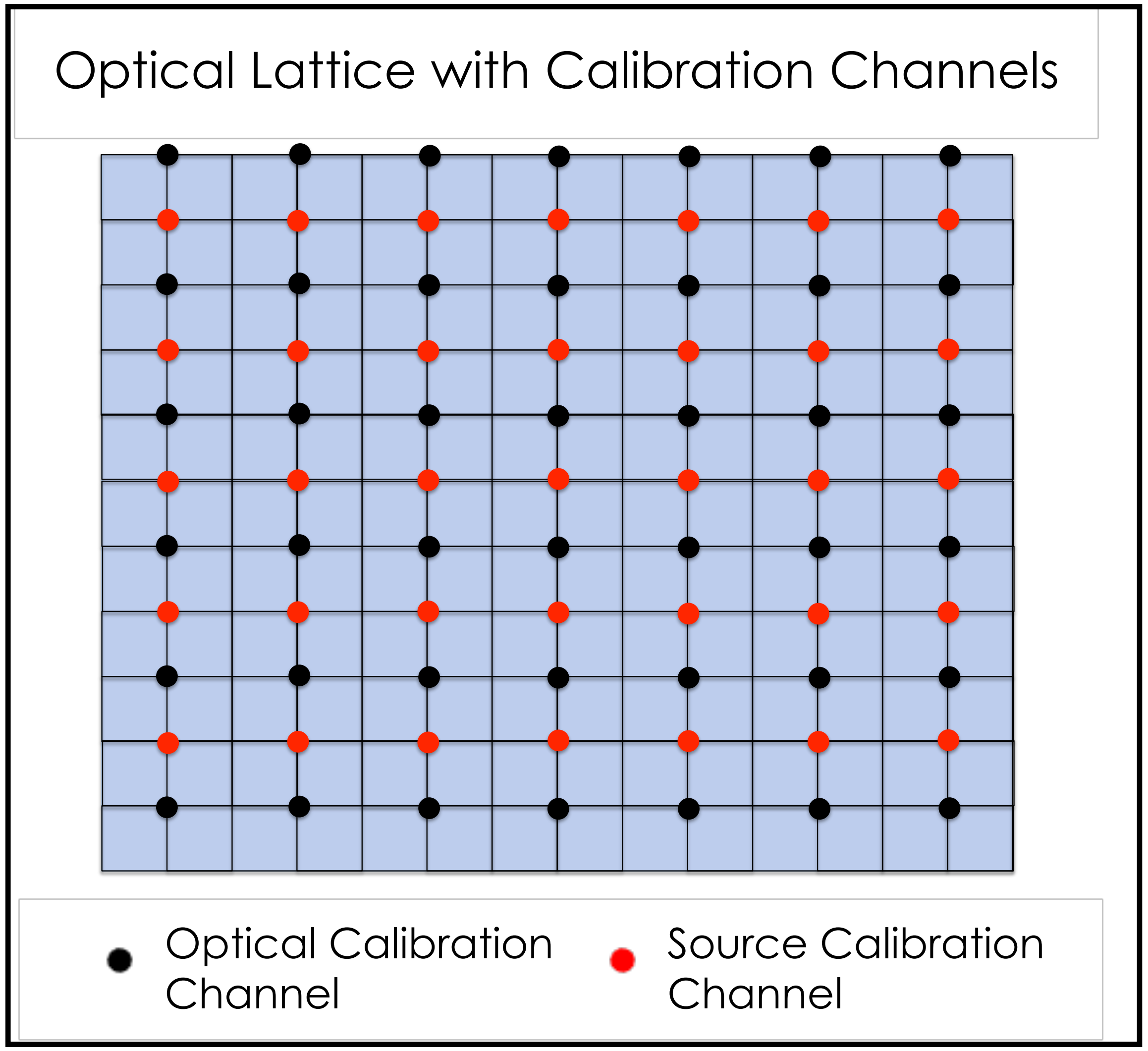
- Strategy to achieve well-understood energy response:
- $E_{rec}(z_{rec},t,s) = A_{ADC\text{-}MeV} * B(s,z_{rec}) * C(t) * D(E_t)$
  - A: ADC-MeV conversion constant
  - B: Equalize energy for point-like depositions in all detector positions
  - C: Stabilize energies over time
  - D: Properly characterize non-linearity and energy loss
- Other calibration needs:
  - Calibrate out global timing offsets between PMT channels
  - Establish time/segment-stable PSD cuts and z_{rec}
  - Ensure stability in signal rate normalization between all segments
- Calibration menu options:
  - User-controlled optical and radioactive calibration sources throughout detector
  - Ambient cosmogenic and radioactive backgrounds

Menu Options: Calibration System

- Pitch in optical lattice allows access for calibration system
- Utilize these axes for optical and radioactive calibration
- Both deployed through teflon tubes in support rods
  - Stationary optical sources
  - Retractable radioactive sources
    - Deploy in many z-positions
    - Swap sources between axes
    - Deploy different gamma sources for extensive energy scale calibration



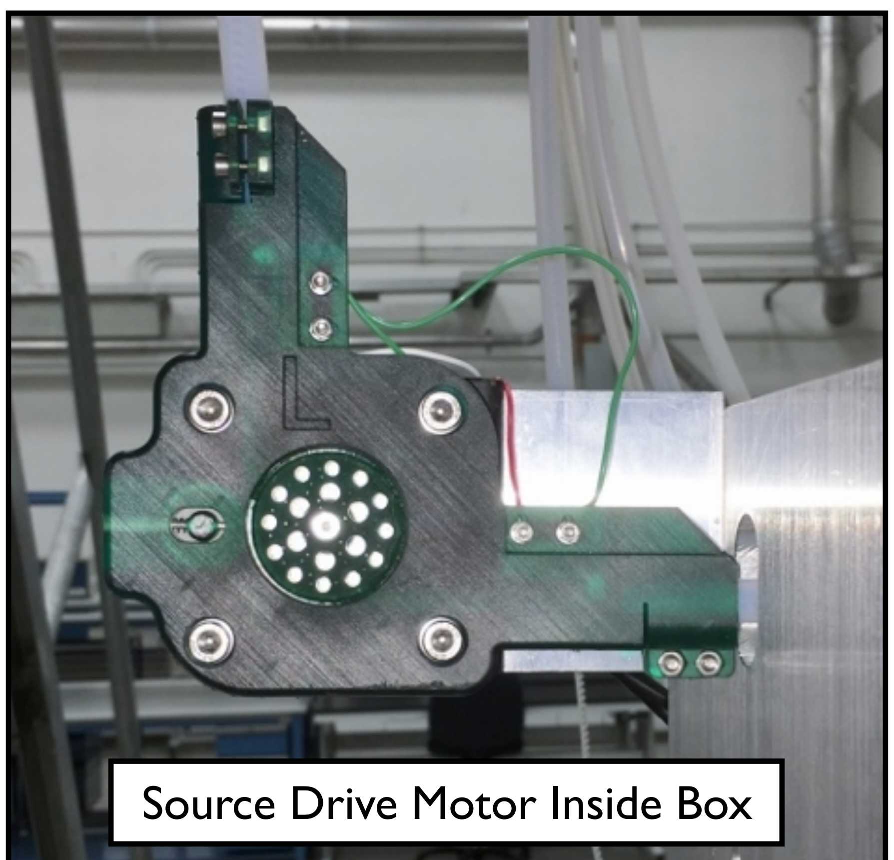


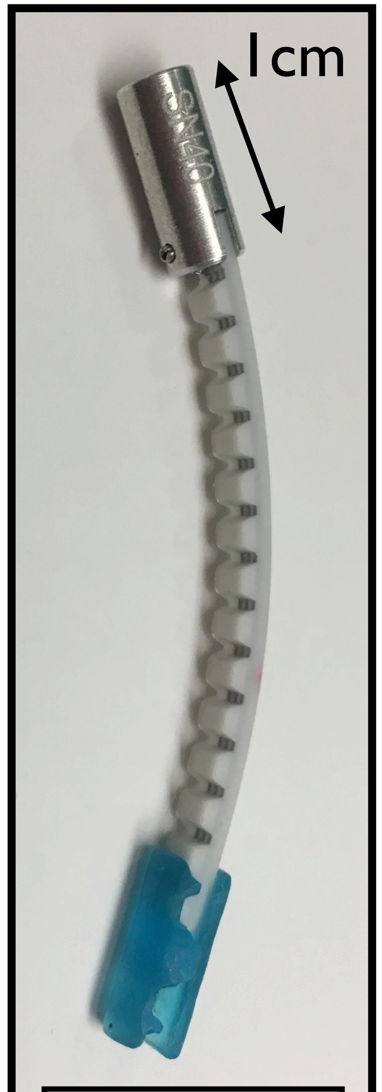


Menu Options: Calibration System

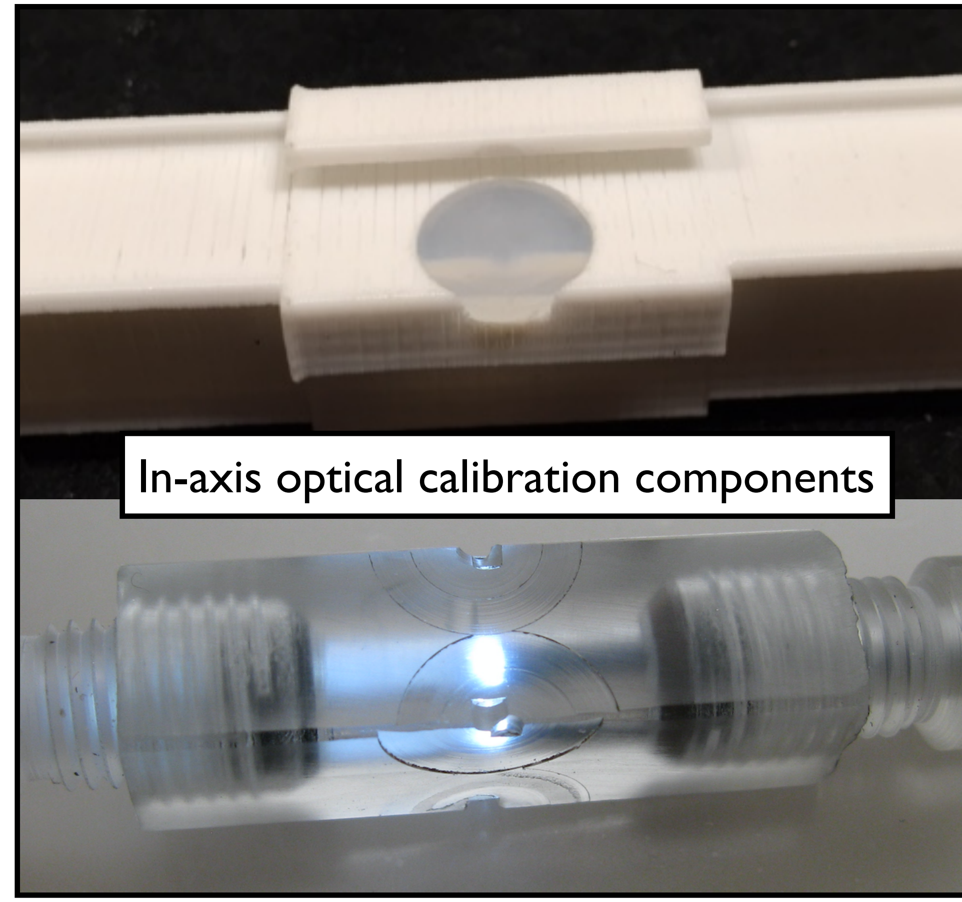
Radioactive Calibration Boxes

Source Drive Motor Inside Box

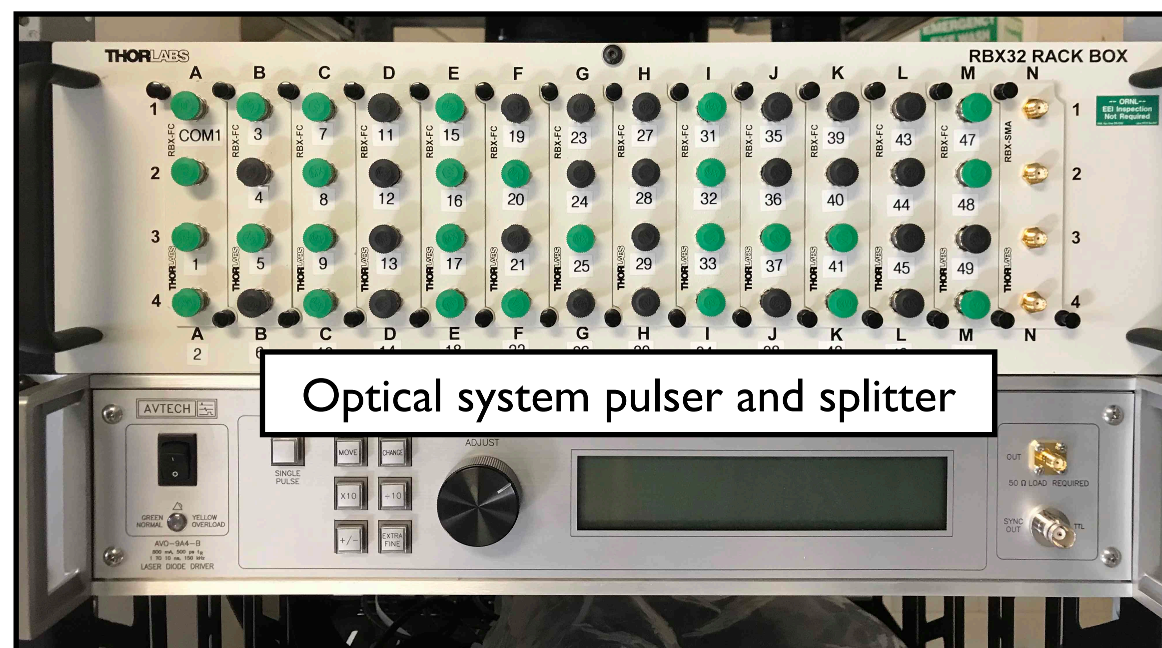




Exchangeable Radioactive Source



In-axis optical calibration components

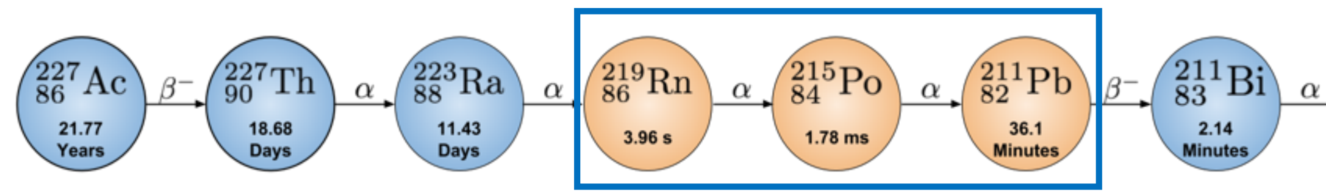


Optical system pulser and splitter

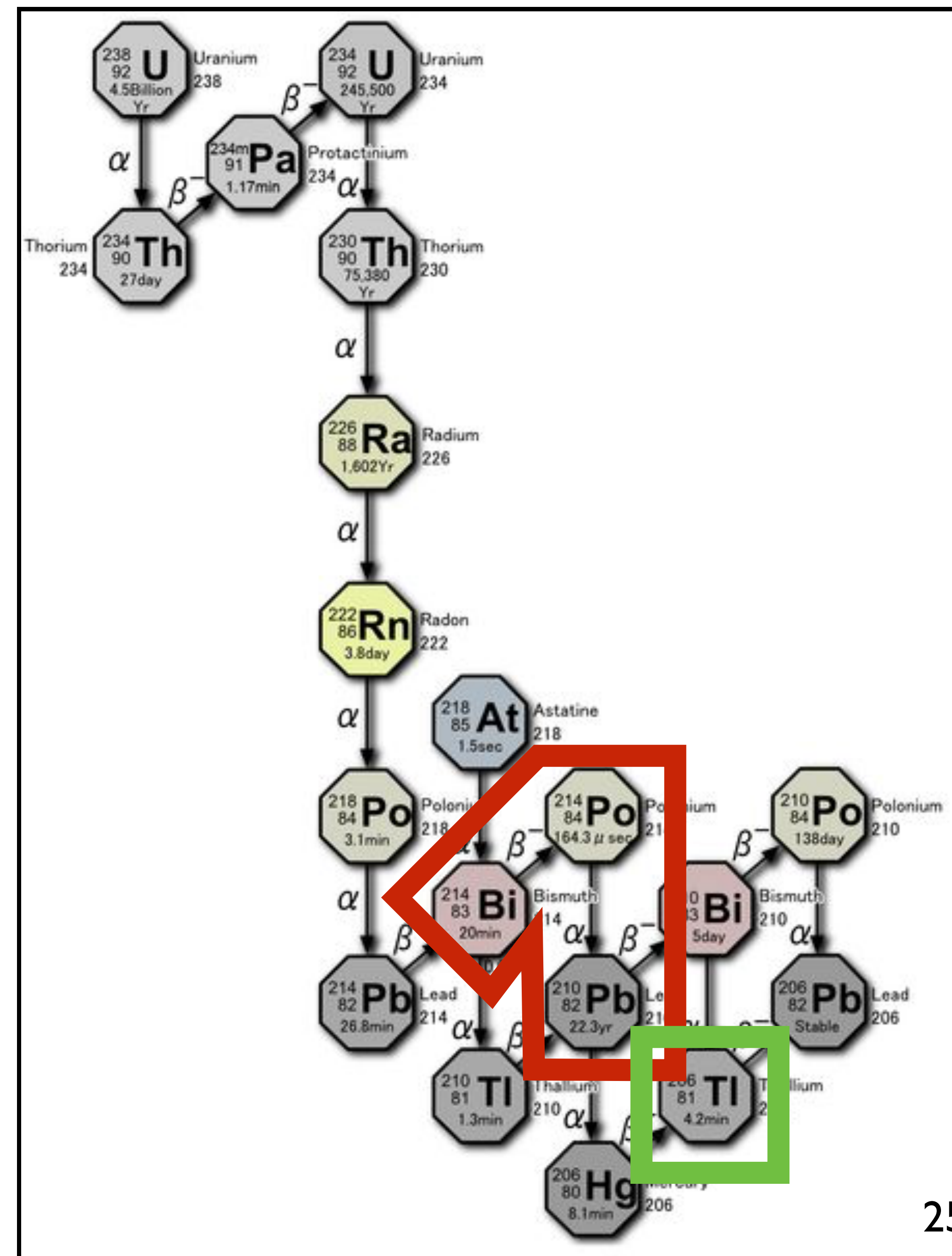
Menu Options: Ambient Calibrations

- A wide variety of intrinsic background peaks also available for calibration purposes

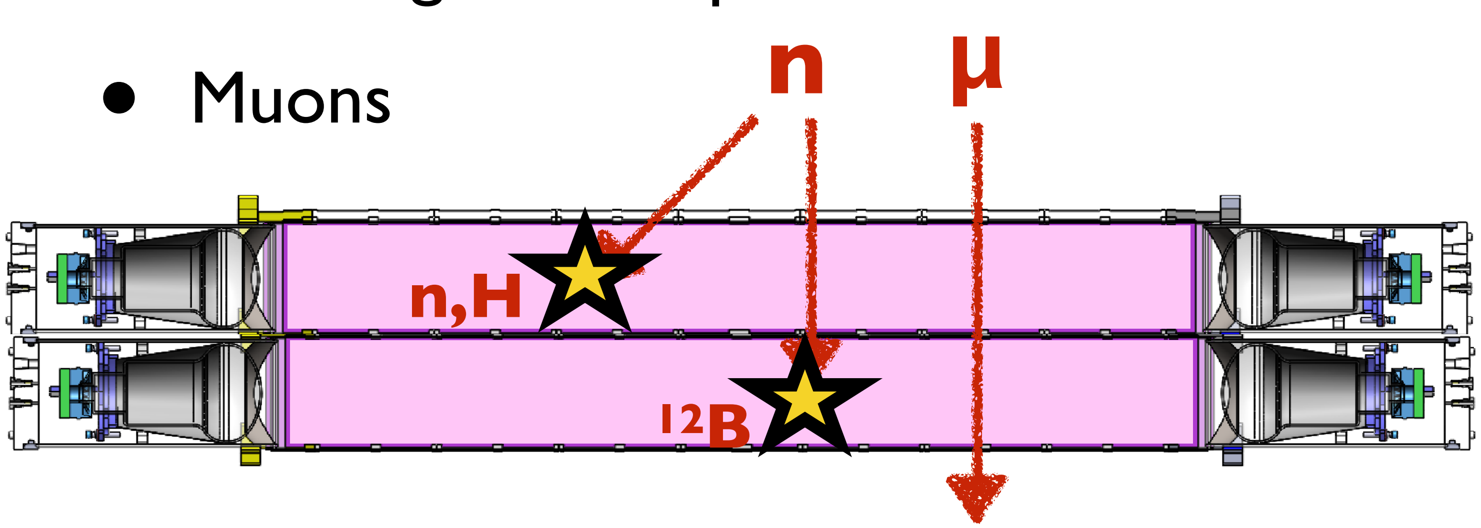
- Intrinsic radioactivity:



  - ^{219}Rn - ^{215}Po (α,α) chain from ^{227}Ac doping
  - Bi - Po (β,α) chain from detector U-Th
  - Radioactive singles: ^{40}K, ^{208}Tl, reactor n-captures on nearby materials



- Cosmic-induced sources:
  - Cosmogenic n-produced isotopes, like ^{12}B
  - Cosmogenic n captures
  - Muons



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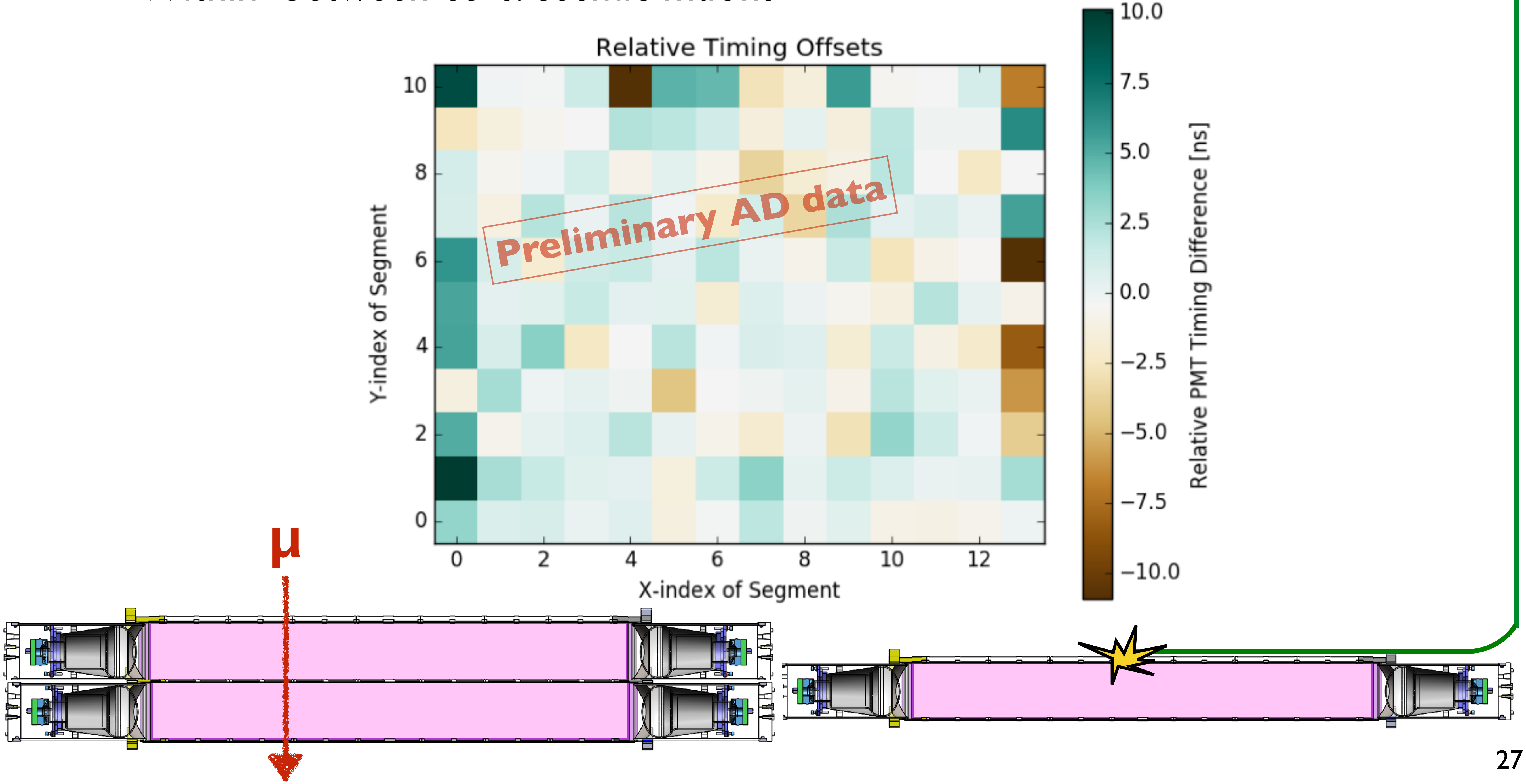
  - C: Stabilize energies over time
  - D: Properly characterize non-linearity and energy loss
- Now let's take a look through each of these steps

Timing Calibration

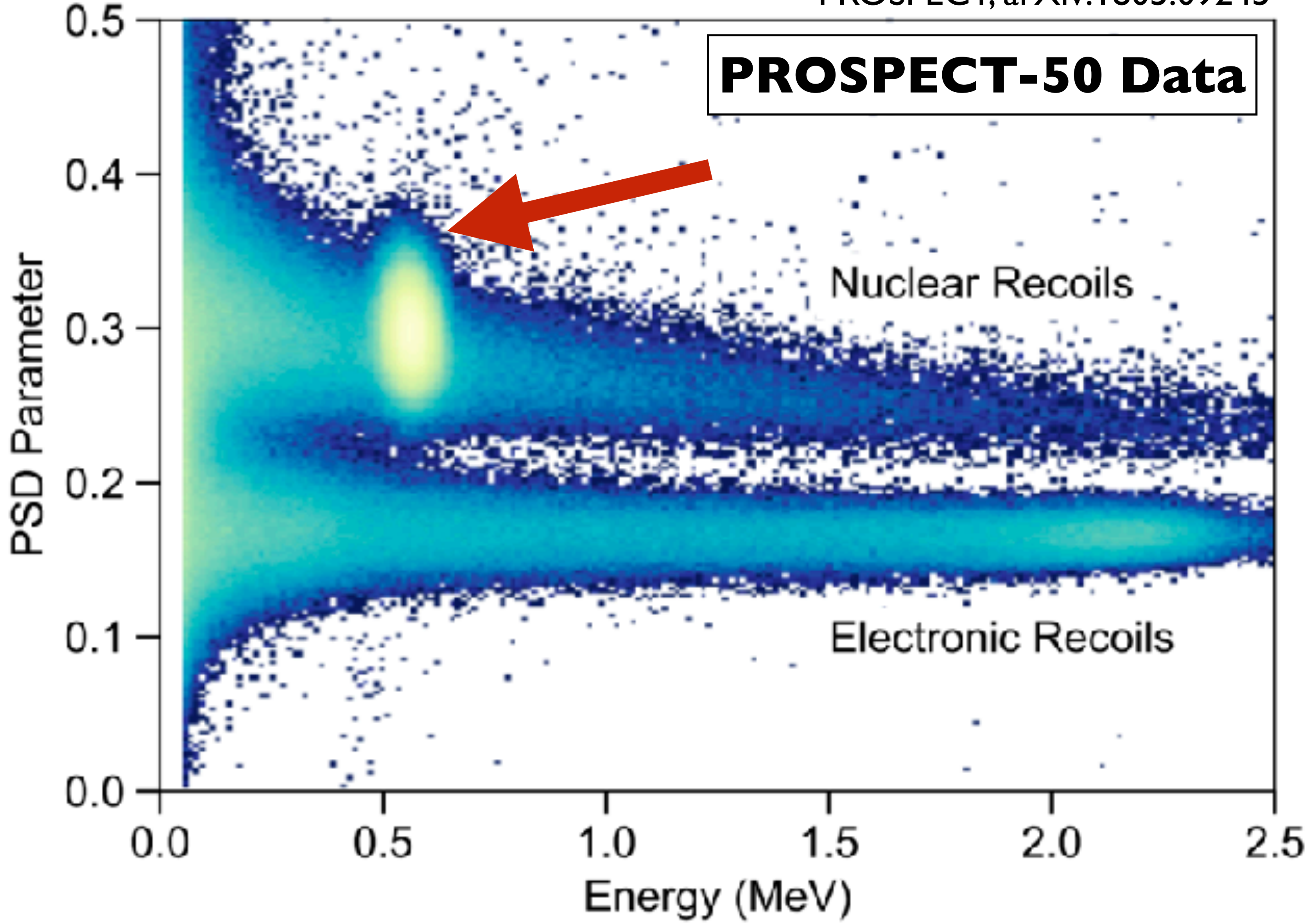
- First step: equalize timing among all PMTs: sub-ns precision
  - Required for absolute z-positions, z-dependent energy scale corrections
  - Within a cell: optical flasher
  - Within+between cells: cosmic muons



A: PE-MeV Conversion

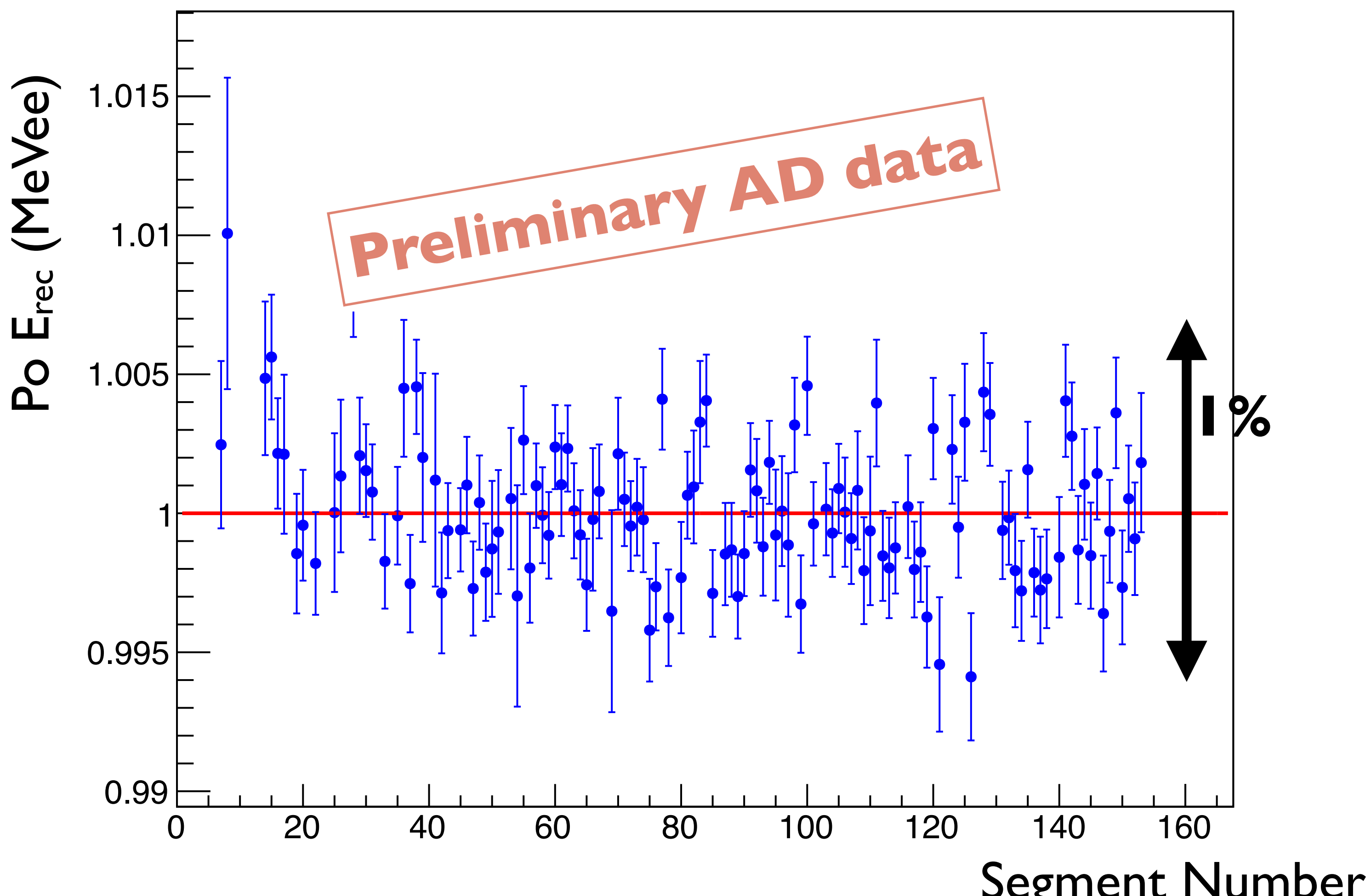
- Convert from ADC to MeV using cosmic n-^{6}Li capture
  - High sample rates and purity, ubiquitous throughout detector
- Note: currently not implementing single-PE calibration
  - Have checked single-PE scale with occasional high-gain runs

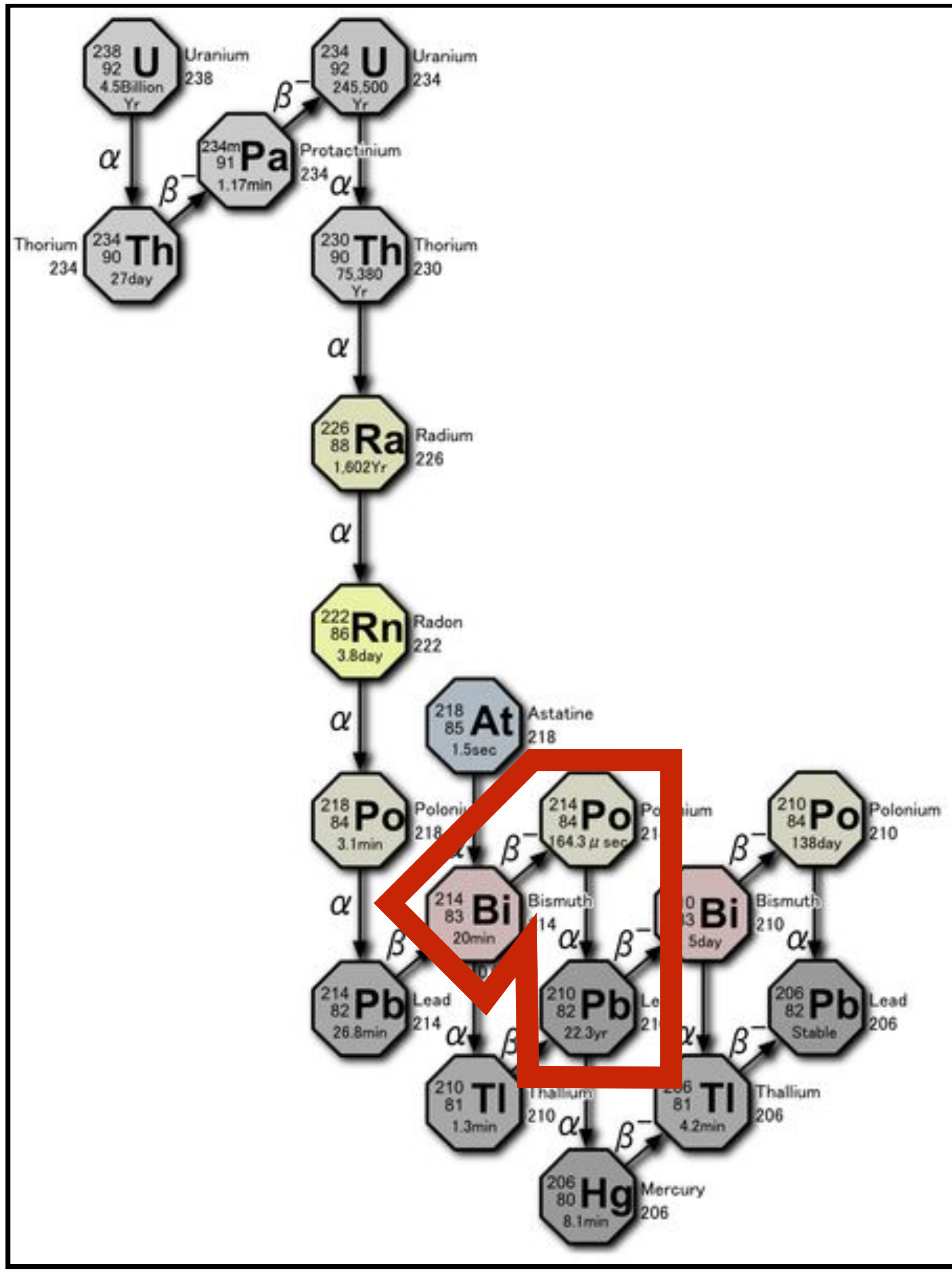
PROSPECT, arXiv:1805.09245



B: Uniformity Versus Position

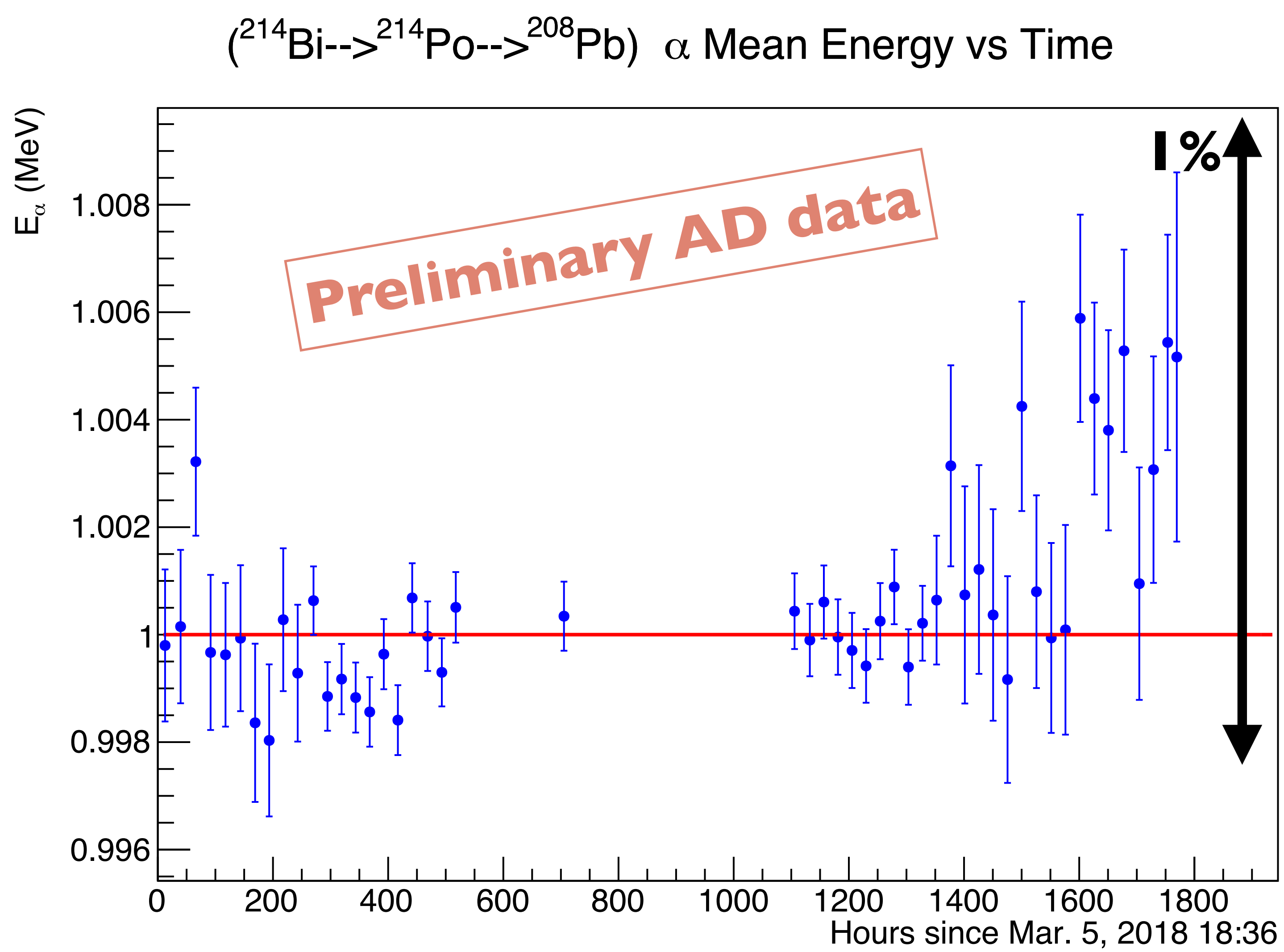
- Reconstruct z-positions using relative timing/charge information from a segment's PMTs: sub-10cm resolution.
  - Done using internal calibration source z-scans and internal geometric features
- Clean nLi peak used for equalizing energy scale at all positions
- Example: Bi-Po decays from detector-intrinsic ^{238}U, ^{232}Th

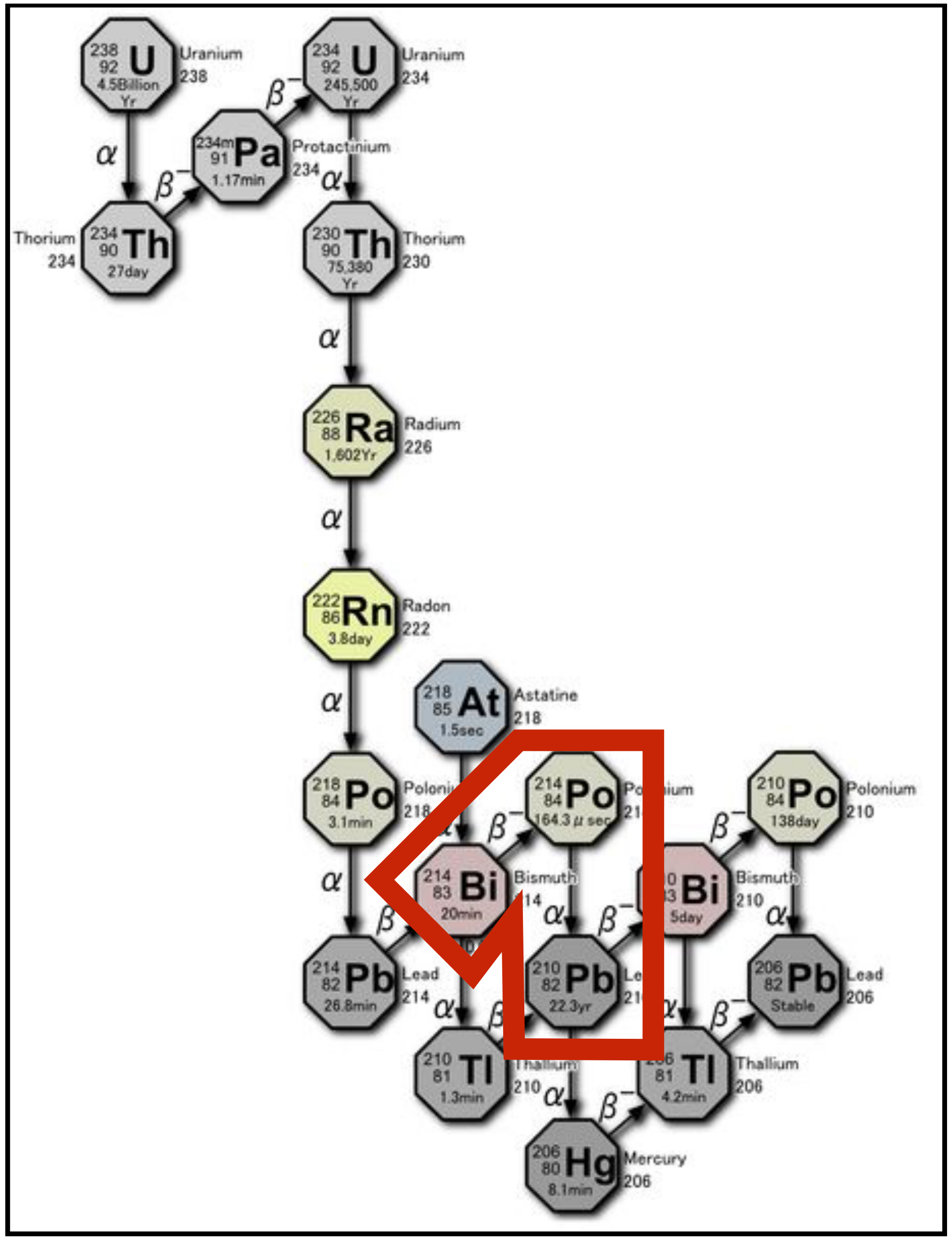




C: Uniformity in Time

- Clean nLi peak used for stabilizing reconstruction over time
- Need checks from other peaks: many available in ambient bkgs.
  - Example: Bi-Po decay chain

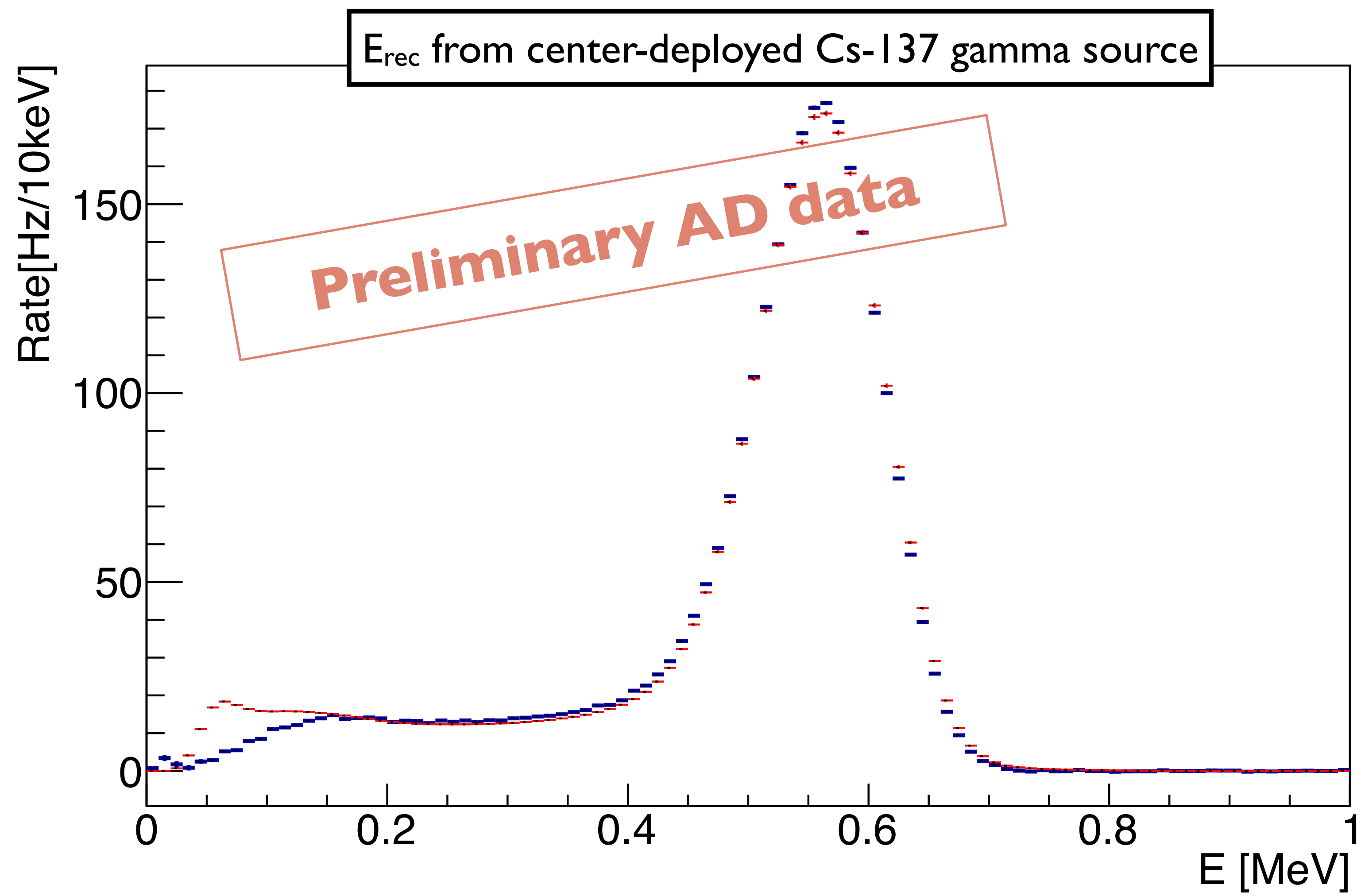




D: Energy Scale Calibration

- **Non-linearity determination:** fit of MC to data while varying MC non-linearity parameters
  - Gamma calibration sources in center
  - Cosmogenic n-produced ^{12}B
  - Can fit spectra for single segments or all combined.
- **Energy loss validation:** data-MC comparison of energy loss vs segment, z
  - ^{22}Na is ideal: contains annihilation gammas, like IBD prompt signal

Source	Decay [keV]
22Na	e^+ -> 511 γ, 1274 γ
60Co	1173 γ, 1332 γ
137Cs	662 γ
252Cf	Spontaneous fission -> n

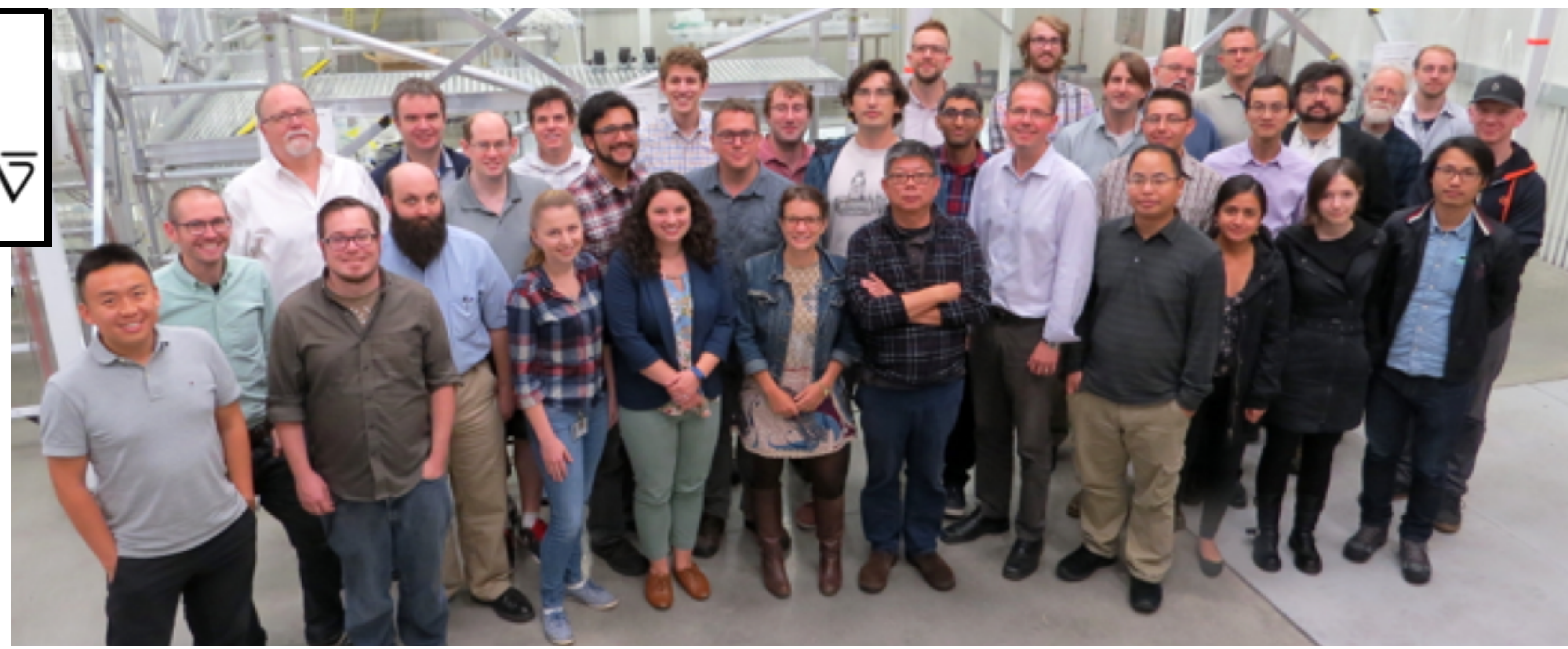


Summary

- PROSPECT is now installed at HFIR and is in data-taking mode
- Many sources are available to produce an energy scale that is well-defined and stable in position and energy
- Have demonstrated excellent position- and time-stability in E_{rec}
- Stay tuned for more data!

PROSPECT

http://prospect.yale.edu/



Funding:

U.S. DEPARTMENT OF ENERGY | Office of Science

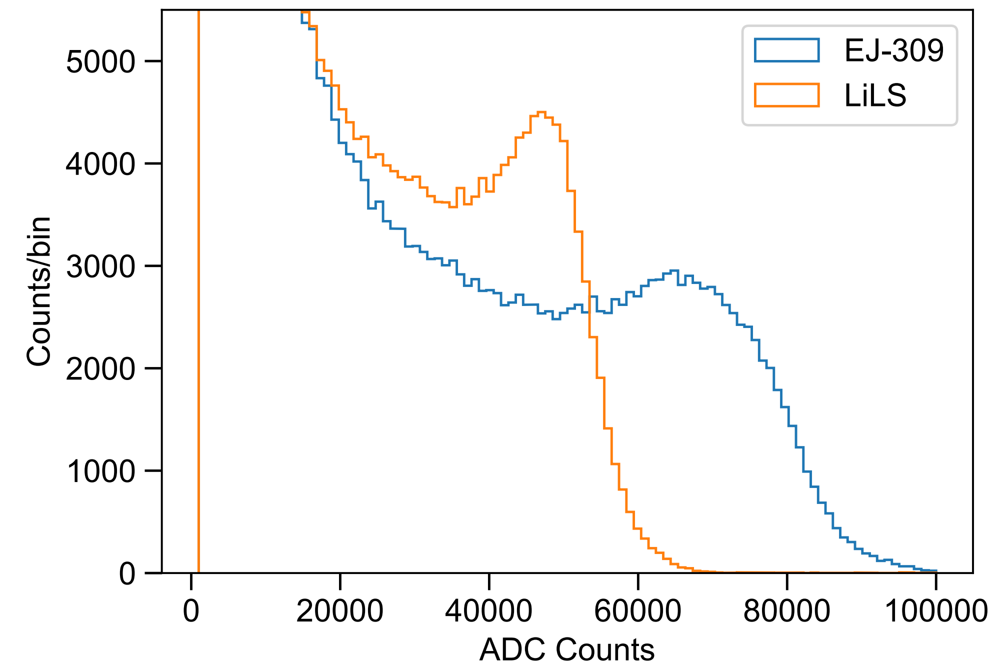
HEISING-SIMONS FOUNDATION

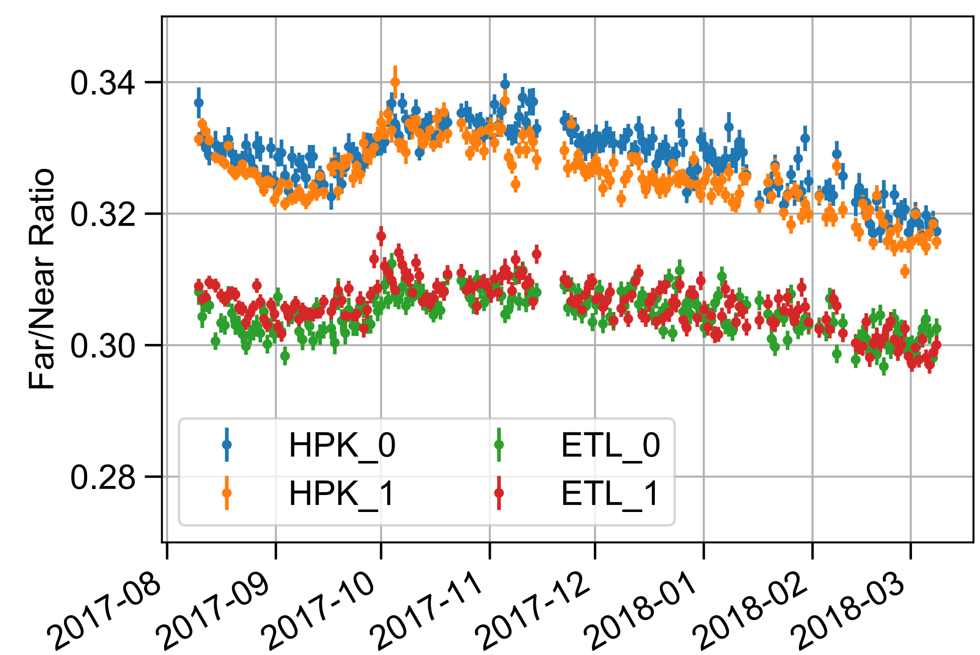
University of Waterloo, Temple University, W&M, Georgia Tech, Le Moyne College, HFIR, Drexel University, Lawrence Livermore National Laboratory, Brookhaven National Laboratory, NIST, Oak Ridge National Laboratory, Yale

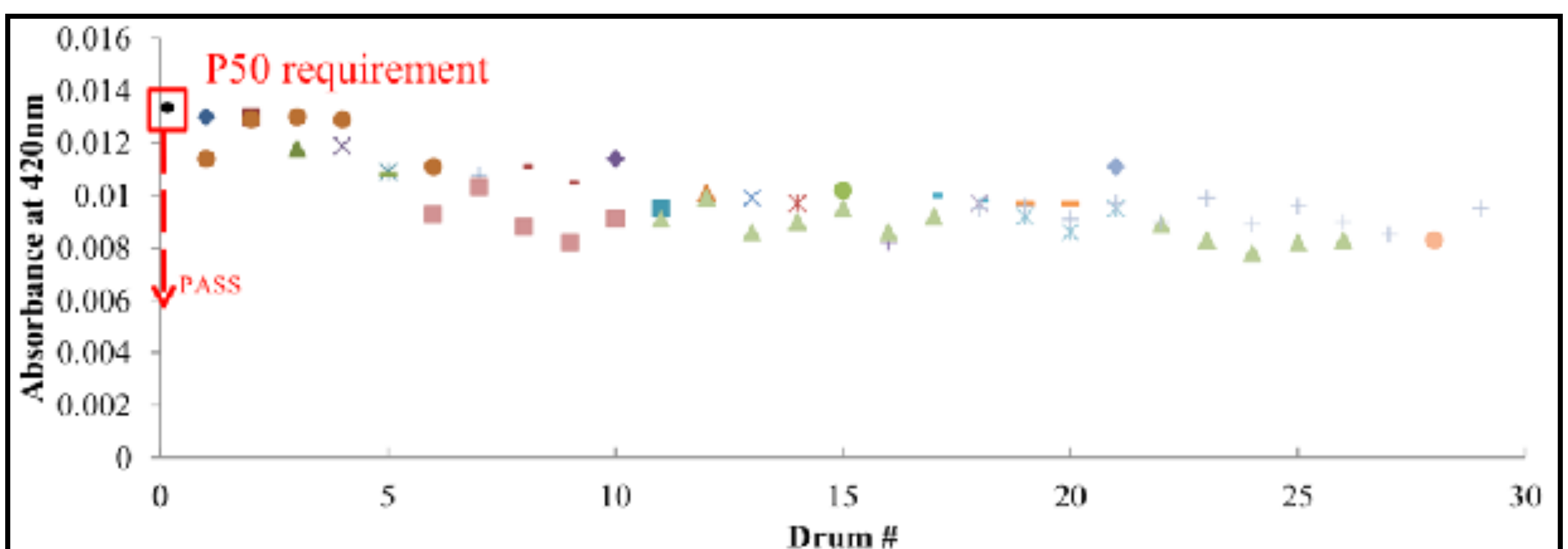
Thanks!

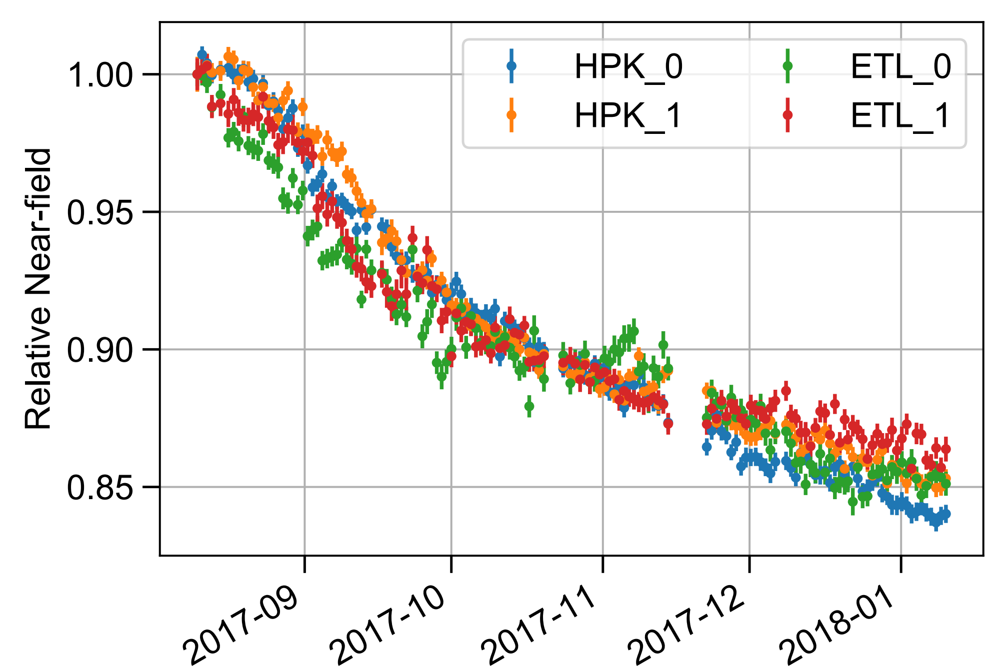
More LS Characterization

- Light Yield ~25% below EJ309
- LiLS shows 15% drop in light yield; consistent with O_2 quench; 10% increase after N_2-bubbling a sample
- Attn. length comparatively stable
- Produced LiLS in 28 batches; QA done on all batches; nearly all passed all QA checks.



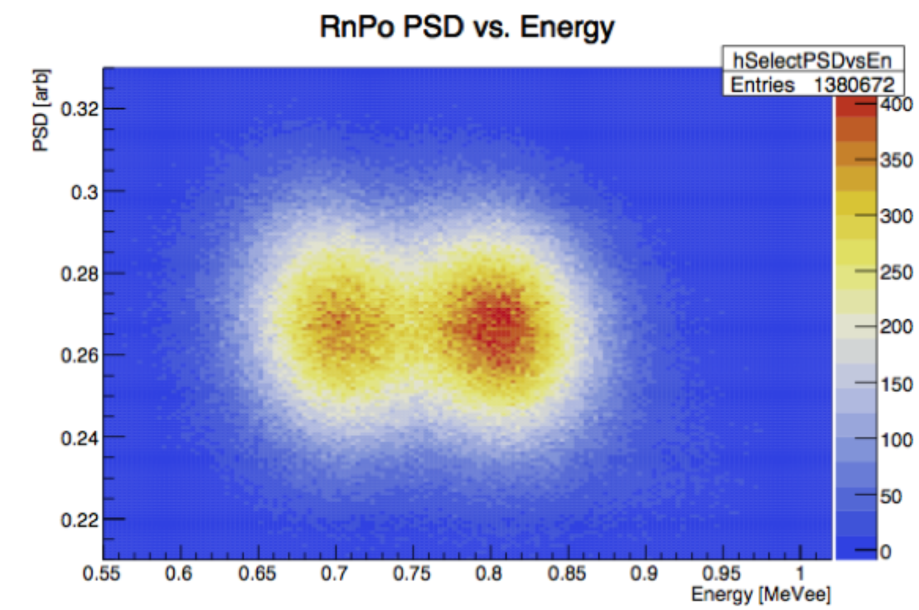


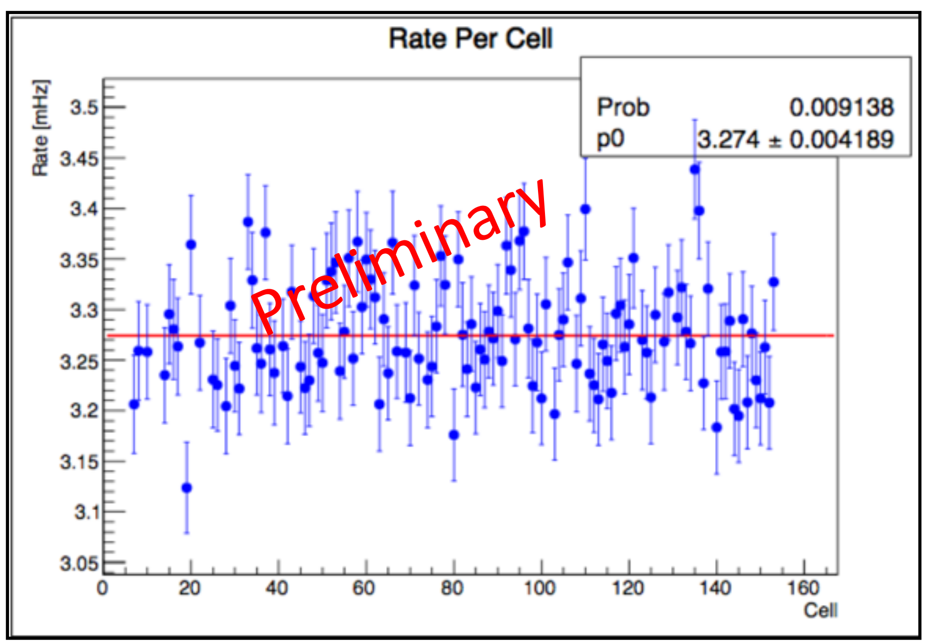


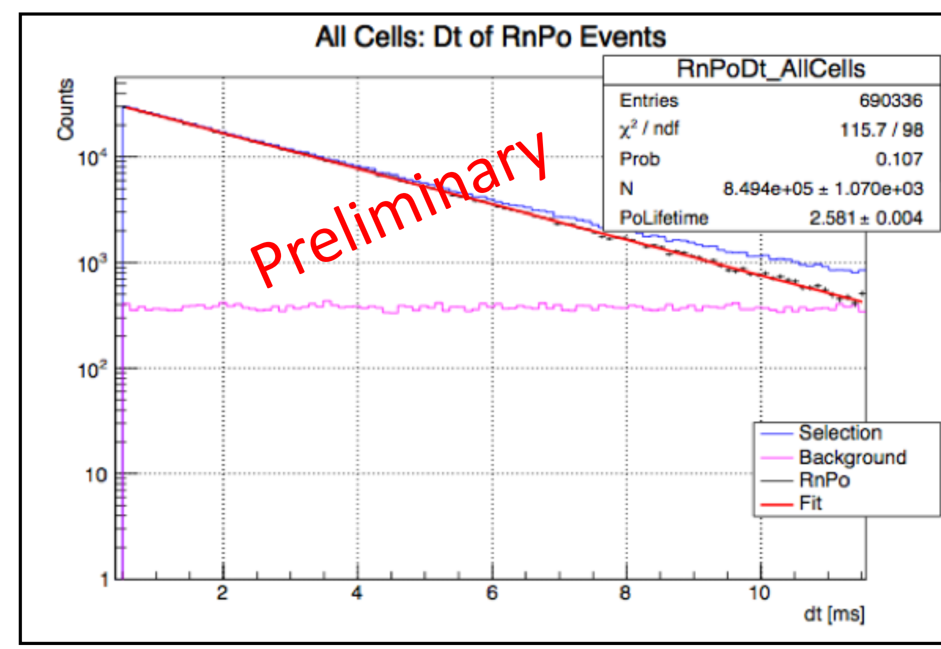


Actinium Doping

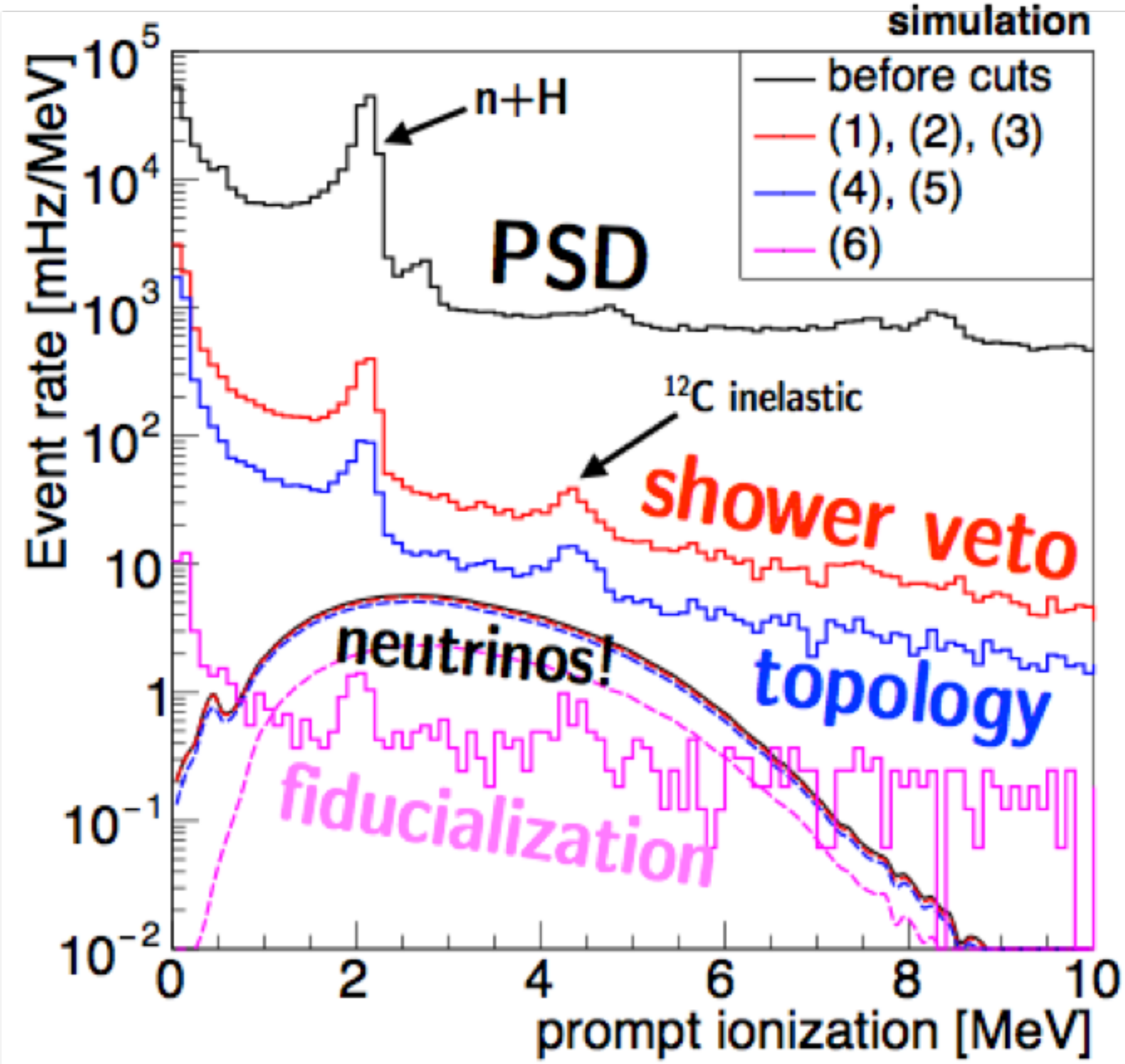
- Relative cell volumes determined by coincident alpha decays in Ac-227 decay chain (Po-215: $T_{1/2} \sim 1.8$ ms)
- Dissolved 0.5 Bq of Ac-227 in detector active volume
- Well separated from background with PSD, energy, and timing cuts
- Efficiency corrected "RnPo" rates proportional to volume

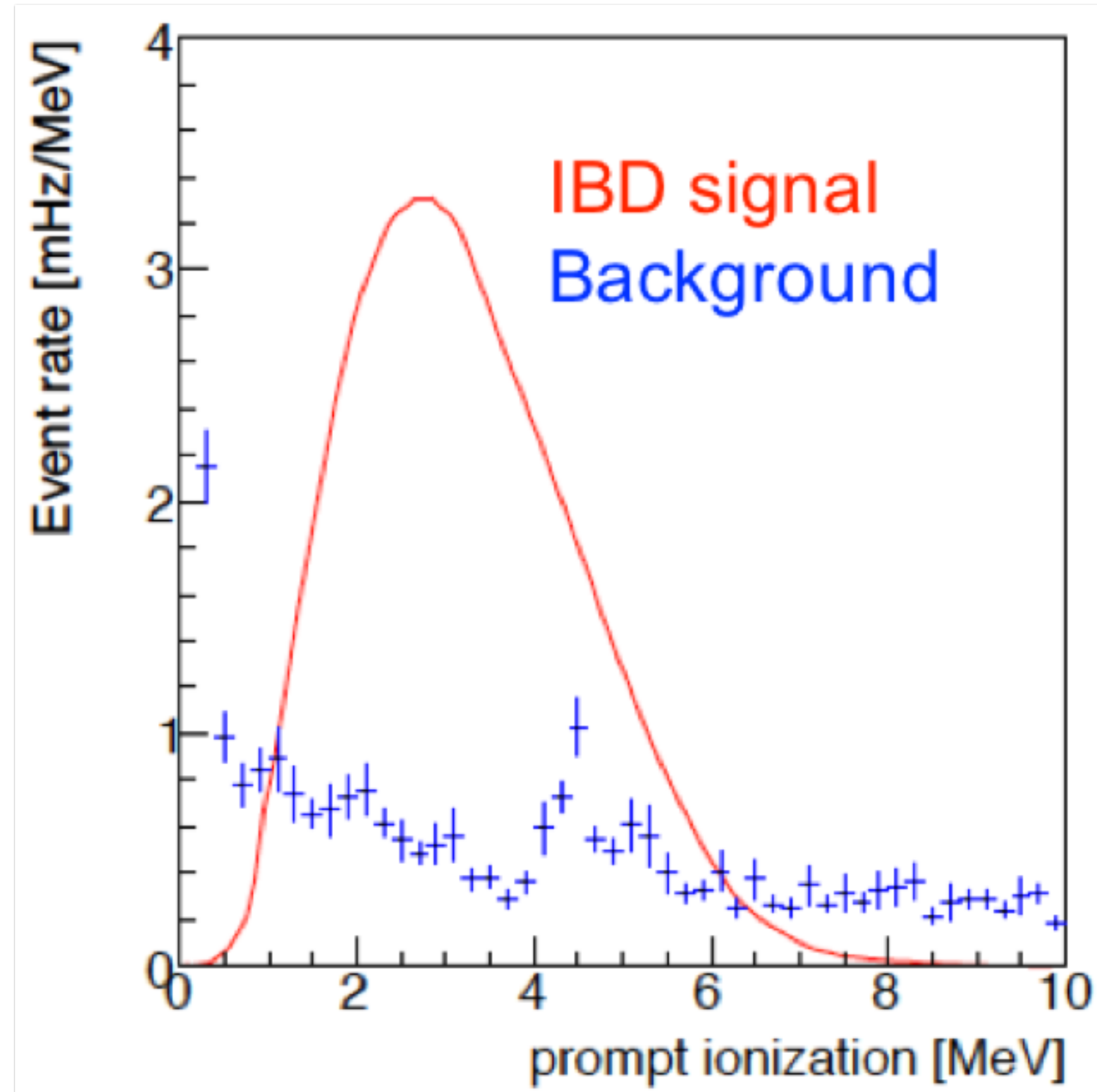






Backgrounds and Expected Rates



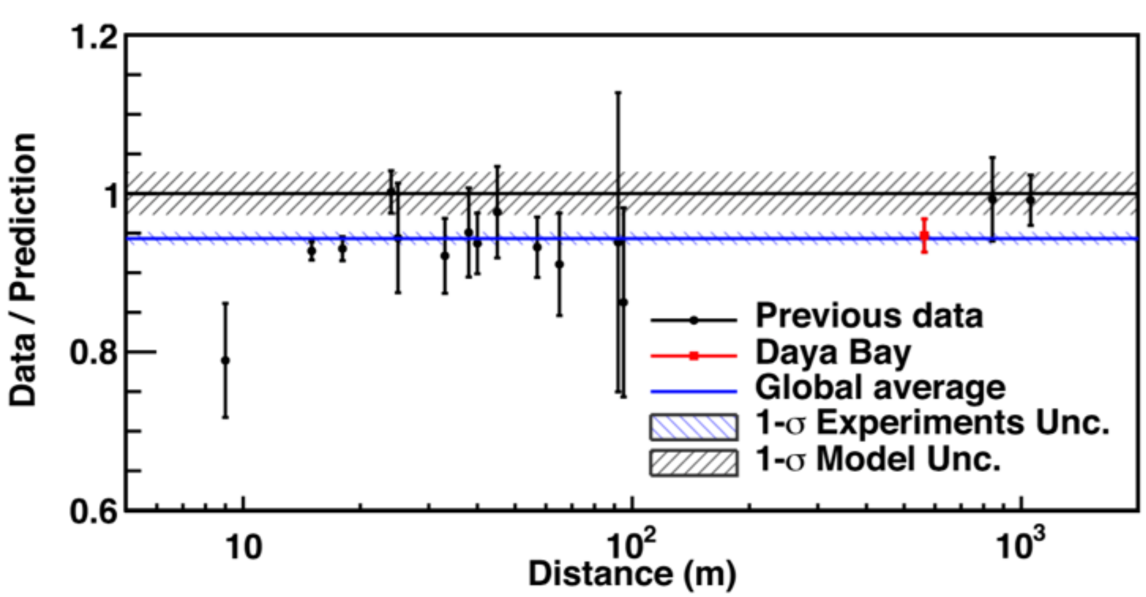


- MC benchmarked by detector prototype data from HFIR site
- cosmogenic backgrounds (solid) and signal (dashed) per cut selection

Physics Motivations

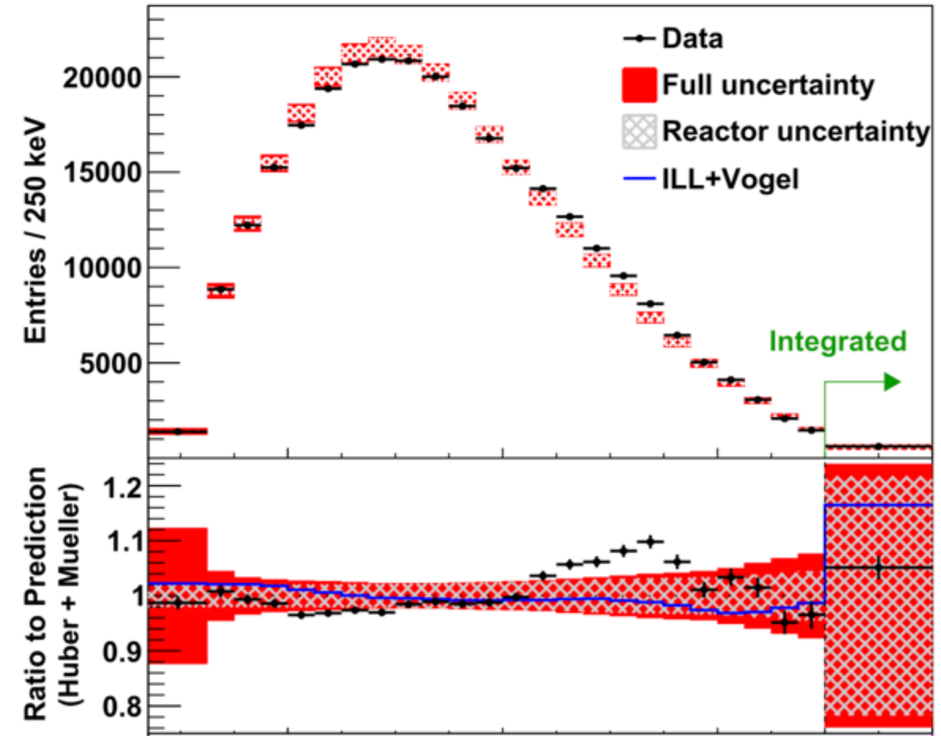
Reactor anti-neutrino anomaly

- New flux predictions (2011) leads to 6% flux deficit for reactor neutrino experiments
- Possible explanations:
  - ~eV scale sterile neutrino
  - flux calculations and/or inputs deficient



The 5-7 MeV "bump"

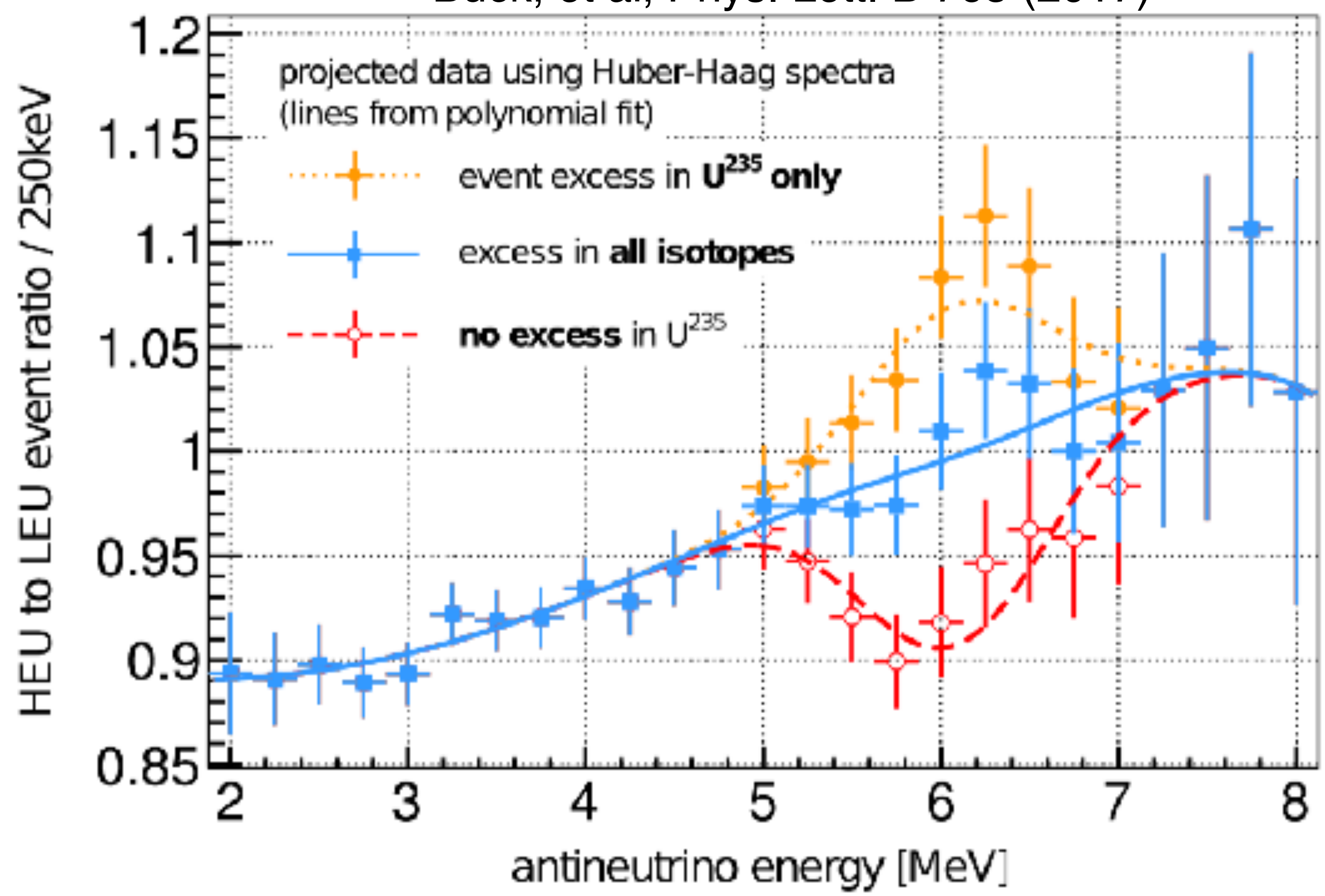
- θ_{13} experiments (Daya Bay, Reno, Double Chooz) all see excess events in 5-7 MeV neutrino energy
- Precise U-235 spectrum helpful for determining source(s) of discrepancy



Example: Only ^{239}Pu, or Only ^{235}U?

- HEU reactors burn only ^{235}U
  - What will the data:model comparison from 4-6 MeV look like from HEU?
    - No bump = bump mainly from U235
    - Larger bump = bump mainly from Pu239
    - Same bump = something else is responsible…
  - Upcoming SBL reactor experiments are crucial
    - PROSPECT: HFIR reactor
    - STEREO: ILL reactor
    - Solid: BR2 reactor
  - Good reason to believe these experiments, combined with θ_{13} experiments, can produce meaningful new constraints.

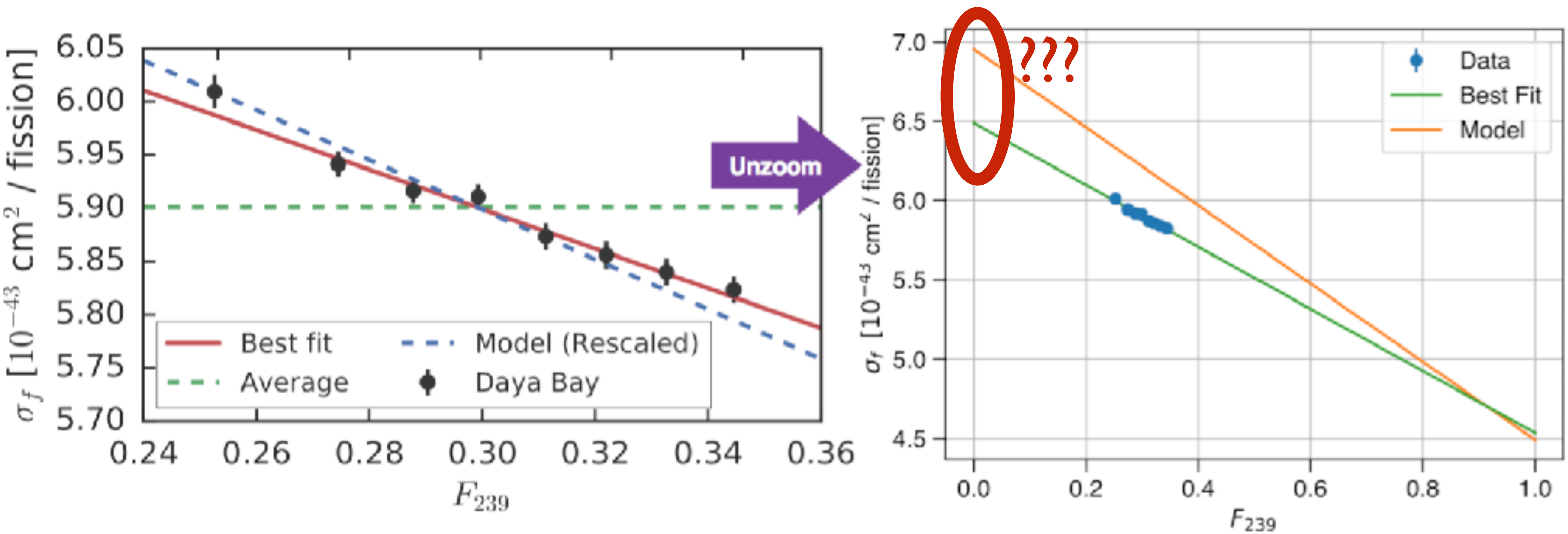
Buck, et al, Phys. Lett. B 765 (2017)



Example: hypothetical STEREO-Double Chooz spectral ratio

Future: New HEU Measurements

- Would be great to probe a wider range of fission fractions



- How about 100% U235, instead of ~50-60%?
  - If ^{235}U is to blame, antineutrino flux deficit should be even larger here
- Enter PROSPECT: at highly-enriched ^{235}U HFIR reactor in Oak Ridge, Tennessee