PROSPECT

PRecision Oscillation and SPECTrum Experiment

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PROSPECT Collaboration

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Outline

- Neutrinos and Nuclear Reactors

  It is difficult to calculate the spectrum and flux

- Detecting Reactor Neutrinos

  Not your "typical" high energy physics experiment

- Reactor Neutrino Oscillations

  First, the good news.

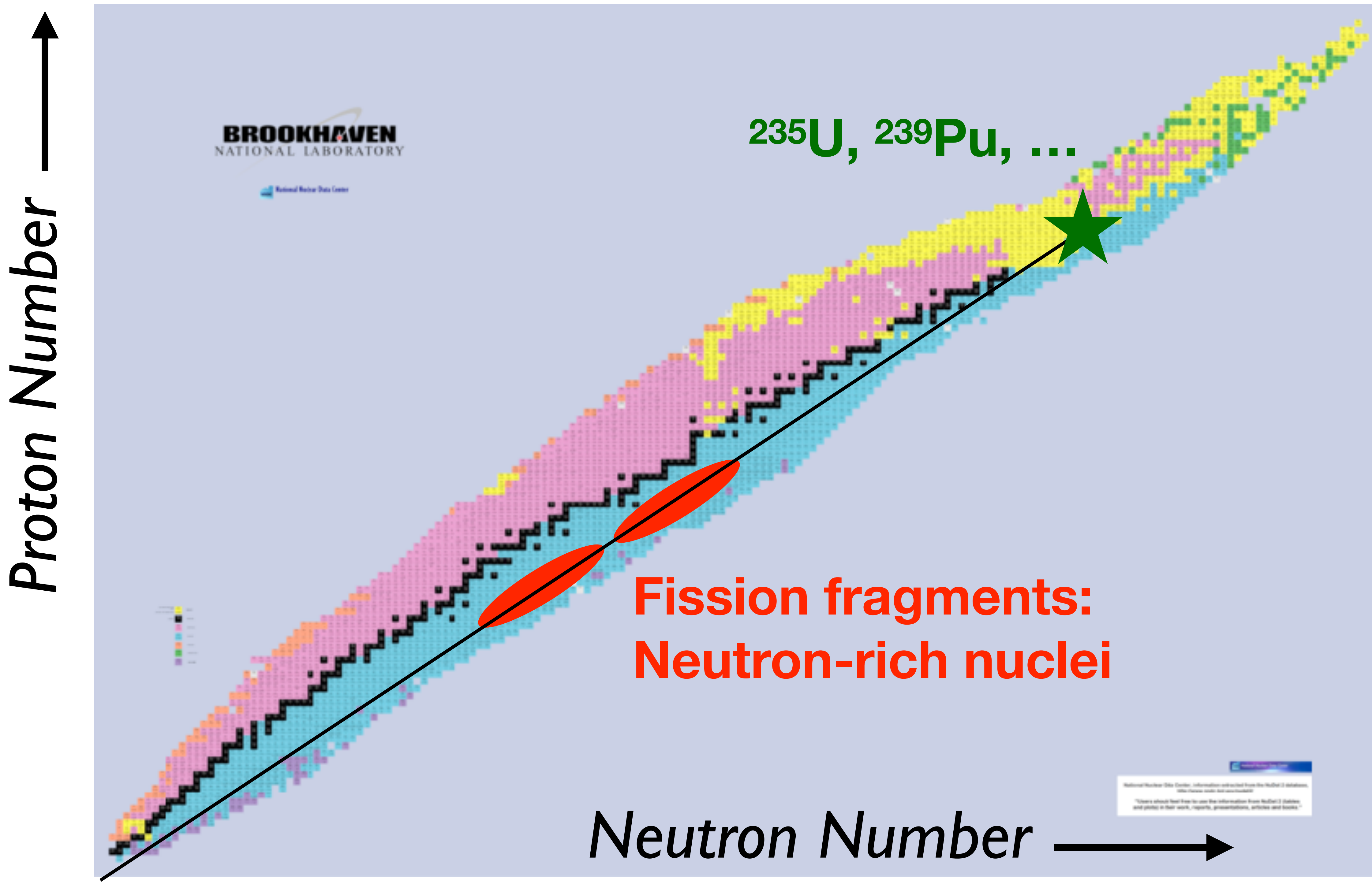
  Then, the bad news: Anomalies

- **PROSPECT**

- Outlook

Neutrinos and Nuclear Reactors

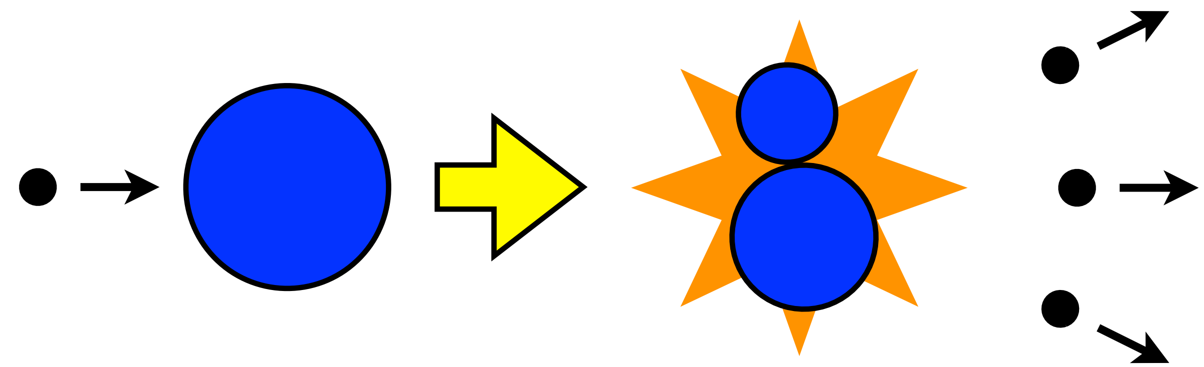
Intense flux of $\overline{\nu}_e$ from β-decay of neutron-rich nuclei



What is the Flux? Spectrum?

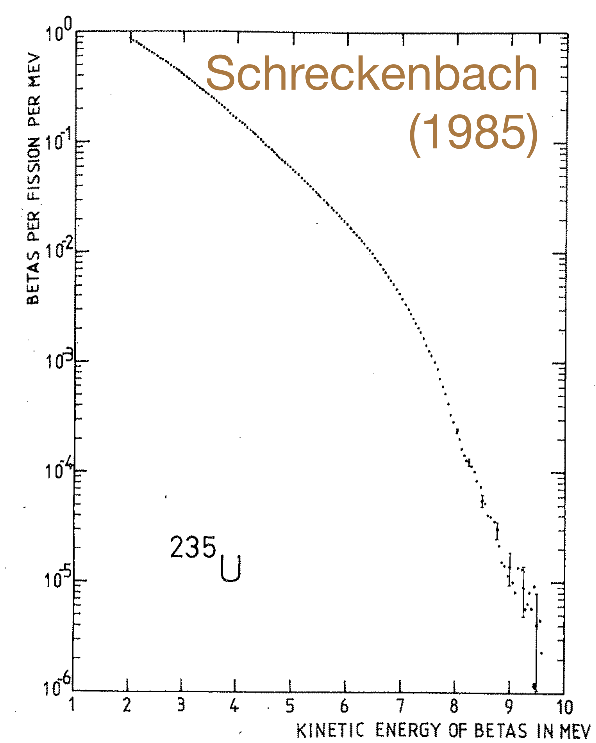
"Reactor Neutrino Spectra", Hayes and Vogel, Ann.Rev.Nucl.Part.Sci. 66 (2016) 219

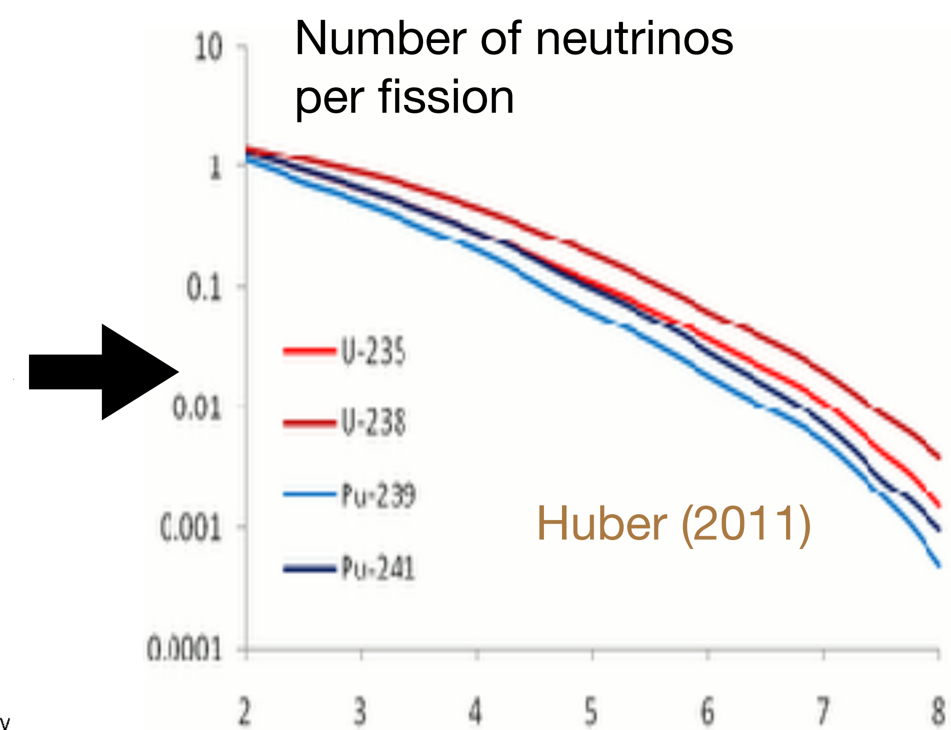
Flux is easy to calculate with ≈20% precision from power output.



Flux is very hard to calculate with 2% precision! Lots of β decay branches, heat from β decay, and the evolution of reactor fuel (especially in nuclear power plant reactors).

Alternative approach: Use "Inversion" of β decay measurements of ^{235}U, ^{239}Pu, …

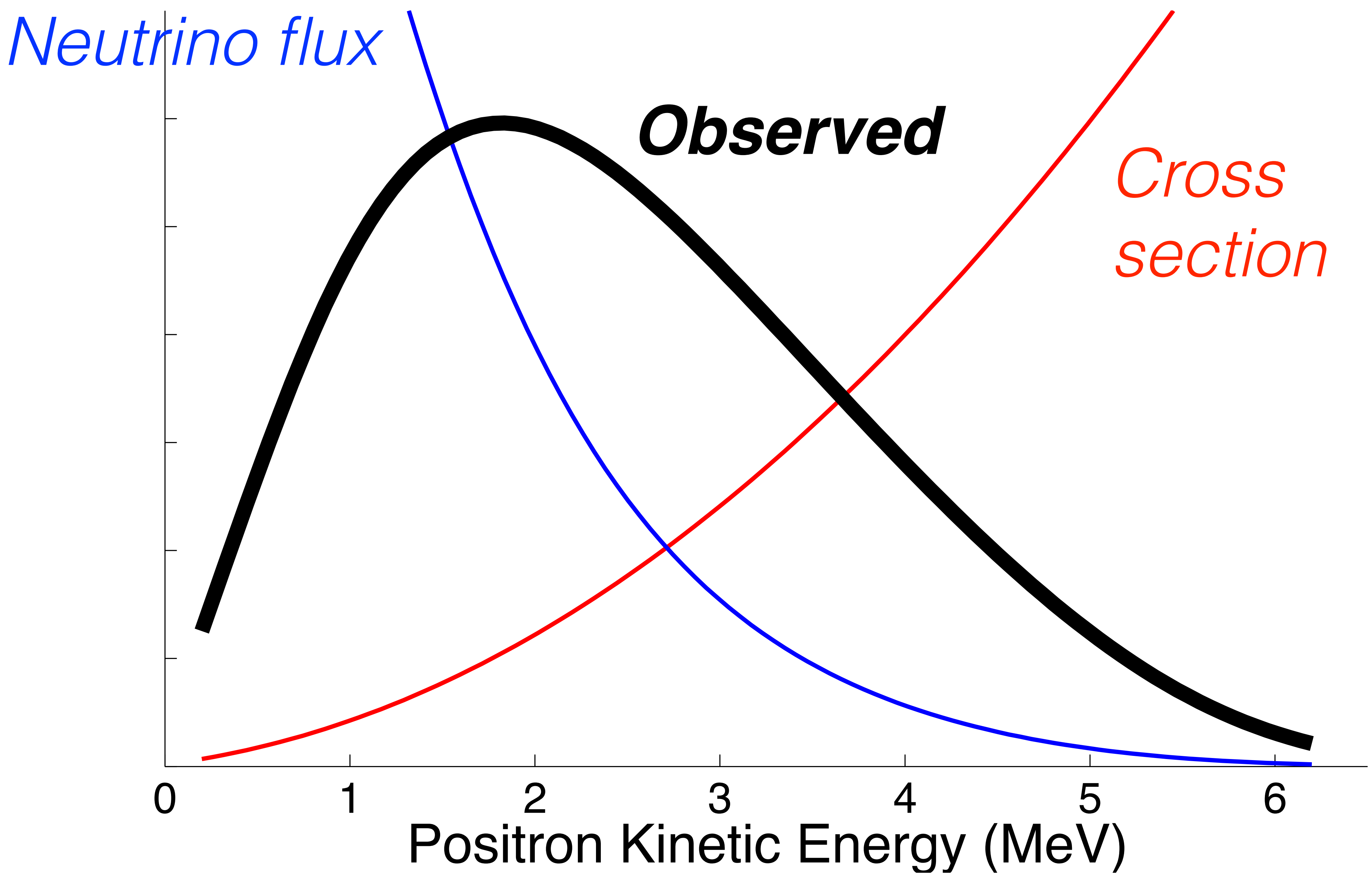




Detecting Reactor Neutrinos

- Reaction: $\overline{\nu}_e + p \rightarrow e^+ + n$ "Inverse Beta Decay" (IBD)
- Liquid scintillator (CH_2) is target (p) and active medium
- Positron energy ⇒ neutrino energy (ignore neutron KE)
- The neutron recoils off protons, thermalizes, and captures providing a delayed coincidence for background rejection.
  - KamLAND: p capture (2.2 MeV photon)
  - Daya Bay: Gd capture (≈8 MeV total photons)
  - **PROSPECT**: ^6Li ($^4He + ^3H$, no photons)
- Backgrounds: Cosmic rays present a serious challenge for **surface-based** reactor antineutrino experiments. Also ambient radioactivity and reactor-associated effects.

The Positron Spectrum

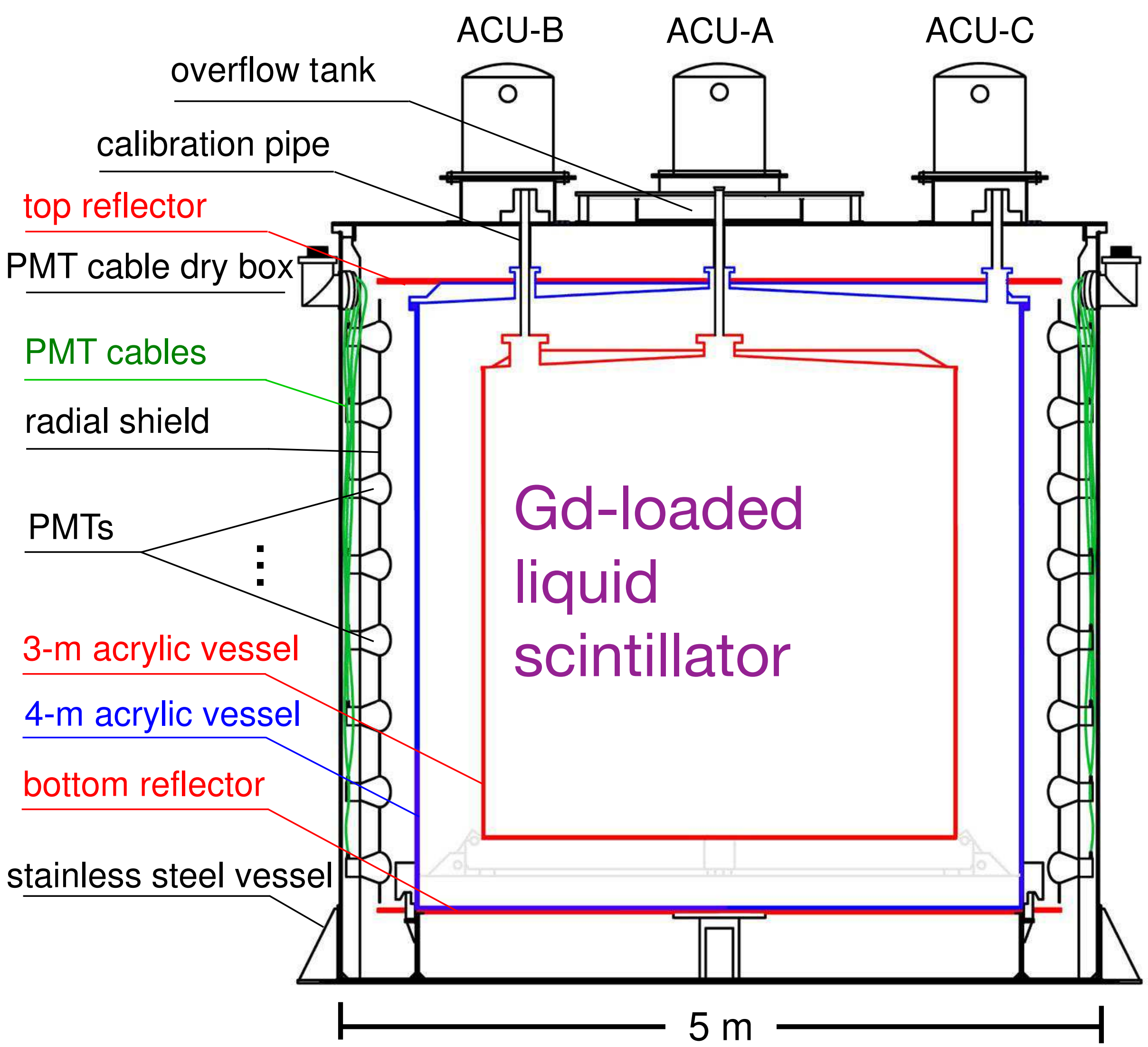


<u>nb</u>: “Prompt” energy adds 1.0 MeV from annihilation photons, and neutrino energy also includes *np* mass difference.

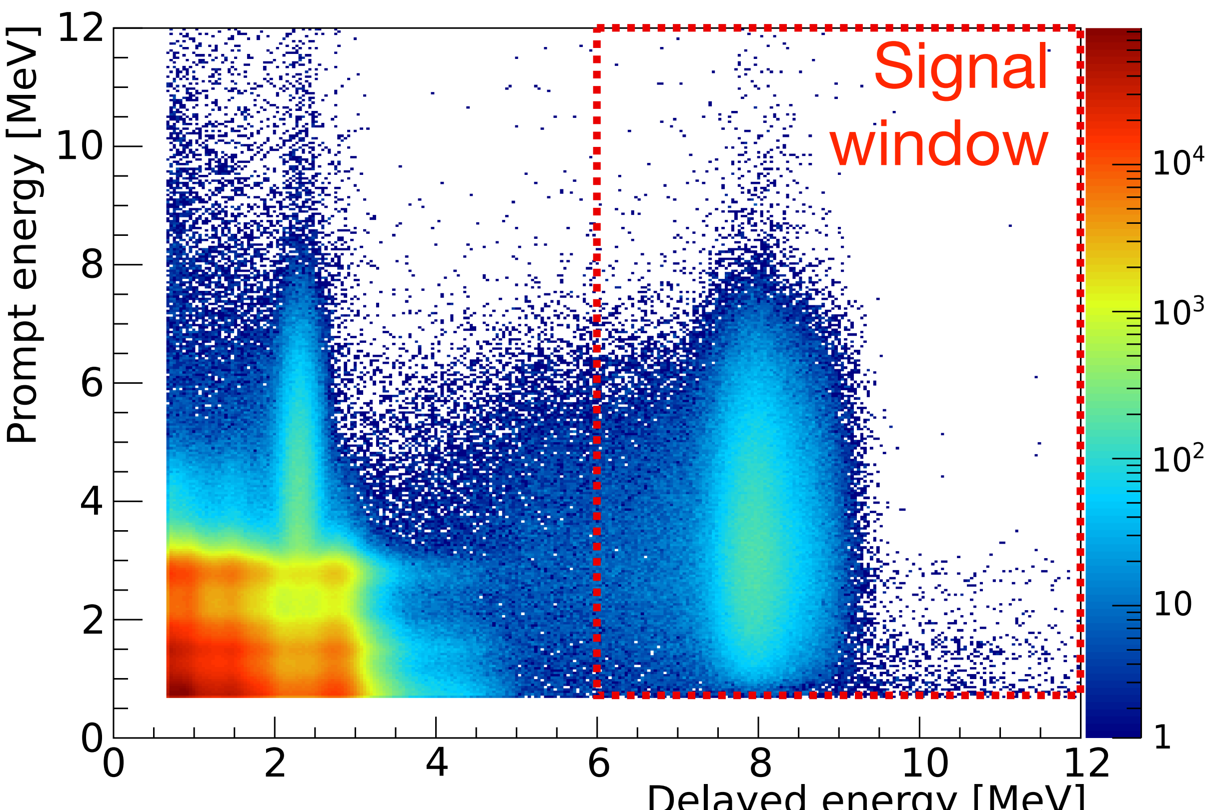
Example: Daya Bay

Well-Shielded Detector at a Nuclear Power Plant

20-Tonne Monolithic Detector



Under ≈100m of rock



Ambient radioactivity

Neutron capture
n+Gd: ≈8 MeV
n+p: 2.2 MeV

Reactor Neutrino Oscillations

Disappearance of Electron Antineutrinos

Write mixing of ν_e and ν_x in terms of energy eigenstates:

$$\begin{aligned} |\nu_e\rangle &= \cos\theta|\nu_1\rangle - \sin\theta|\nu_2\rangle \\ |\nu_x\rangle &= \sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \end{aligned}$$

Very small neutrino masses:

$$E_{1,2} = \left[p^2 + m_{1,2}^2\right]^{1/2} \approx p + \frac{m_{1,2}^2}{2E}$$

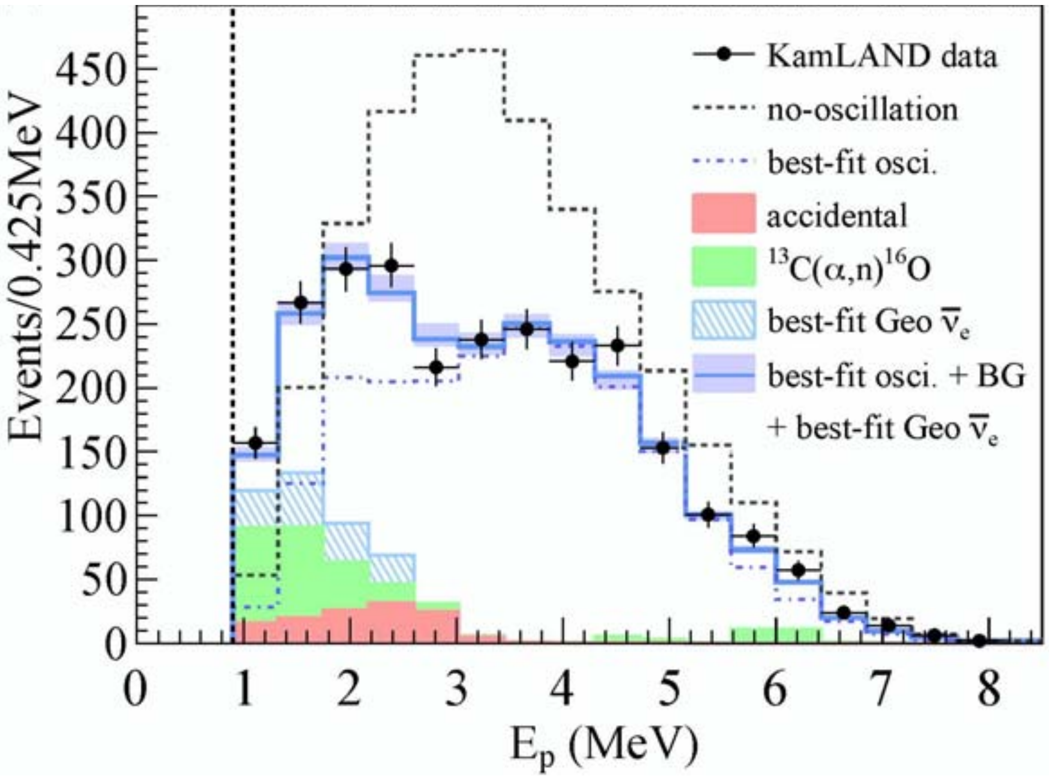
Use basic Quantum Mechanics to propagate neutrinos over a distance L, and calculate the probability:

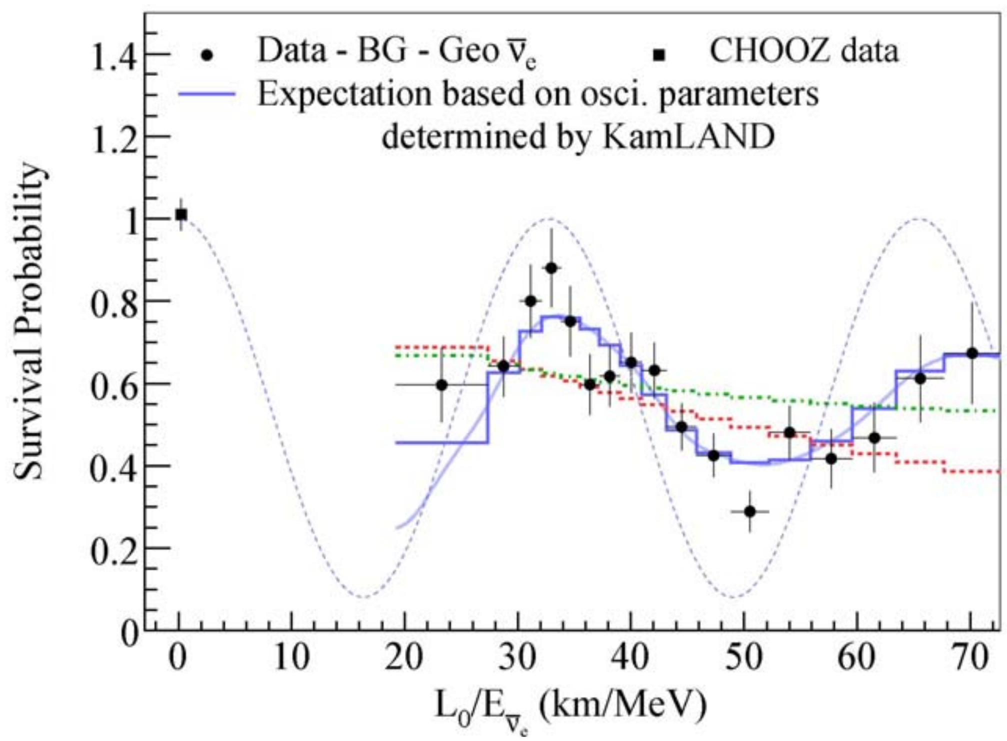
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2\left[1.27\Delta m^2(\text{eV}^2)\frac{L}{E}\left(\frac{\text{m}}{\text{MeV}}\right)\right]$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

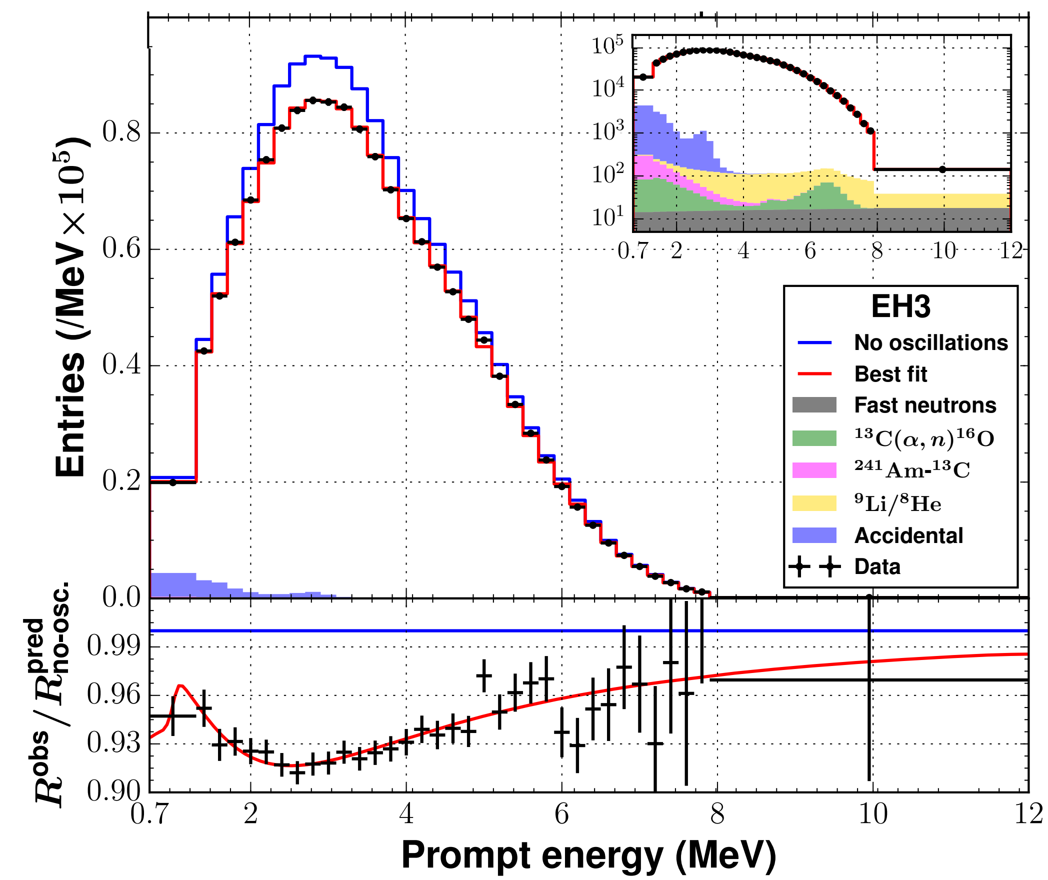
Examples: θ_{12} and θ_{13}

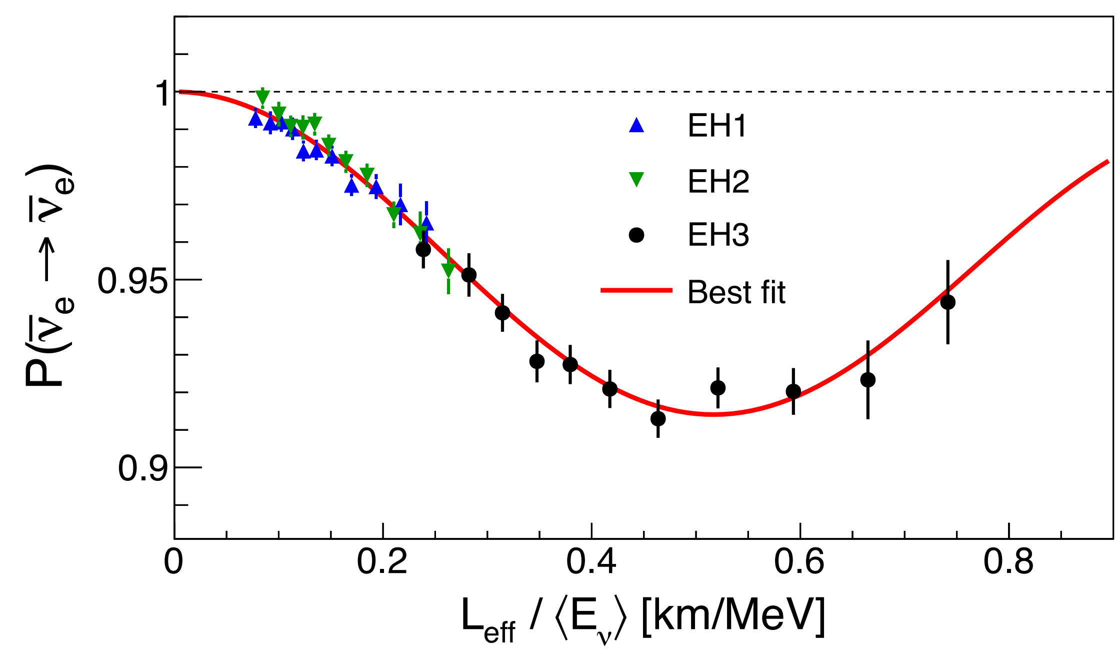
KamLAND: θ_{12}





Daya Bay: θ_{13}





Status: The Good News

- Mixing angles θ_{12}, θ_{13}, and θ_{23} are all known

  Reactor and beam experiments all contribute

- Mass^2 differences are well measured

  Everything appears to be consistent

- CP Phase δ "looks like" it is nonzero

  Will be pinned by T2K, NOvA, and DUNE

- Mass hierarchy "looks like" it is normal

  Will be pinned by JUNO, NOvA, and DUNE

Status: Anomalies

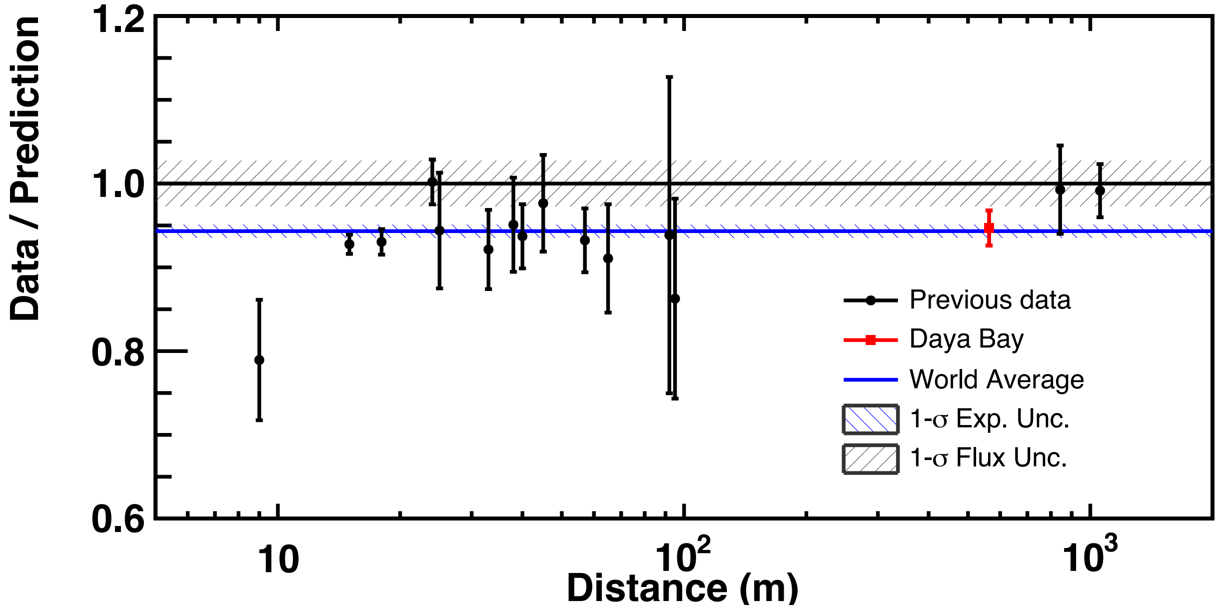
These show up mainly in reactor experiments

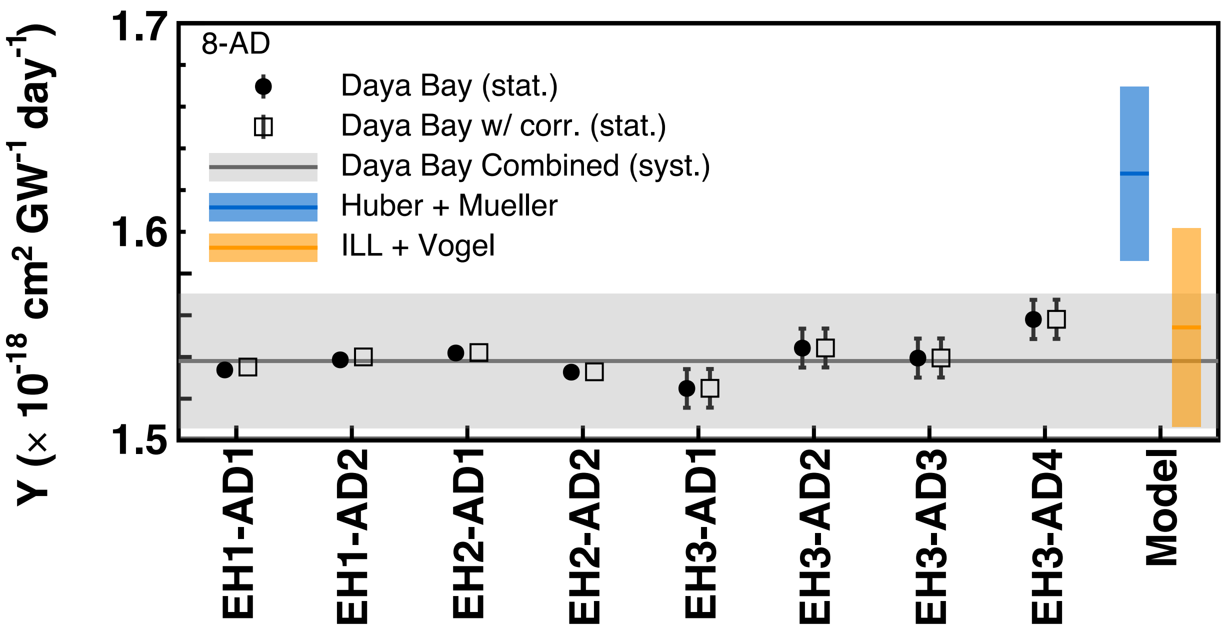
- The flux is 6% smaller than calculations
  aka The "Reactor Neutrino Anomaly", where the most recent calculations disagree with experiment
  ➥ *Interpret in terms of "Sterile Neutrinos"?*

- The "bump" at 5 MeV in reactor spectra
  Unexpected feature that shows up in all of the high statistics reactor neutrino experiments (Double Chooz, RENO, and Daya Bay)
  ➥ *A clue to the Reactor Neutrino Anomaly?*

Reactor Neutrino Anomaly

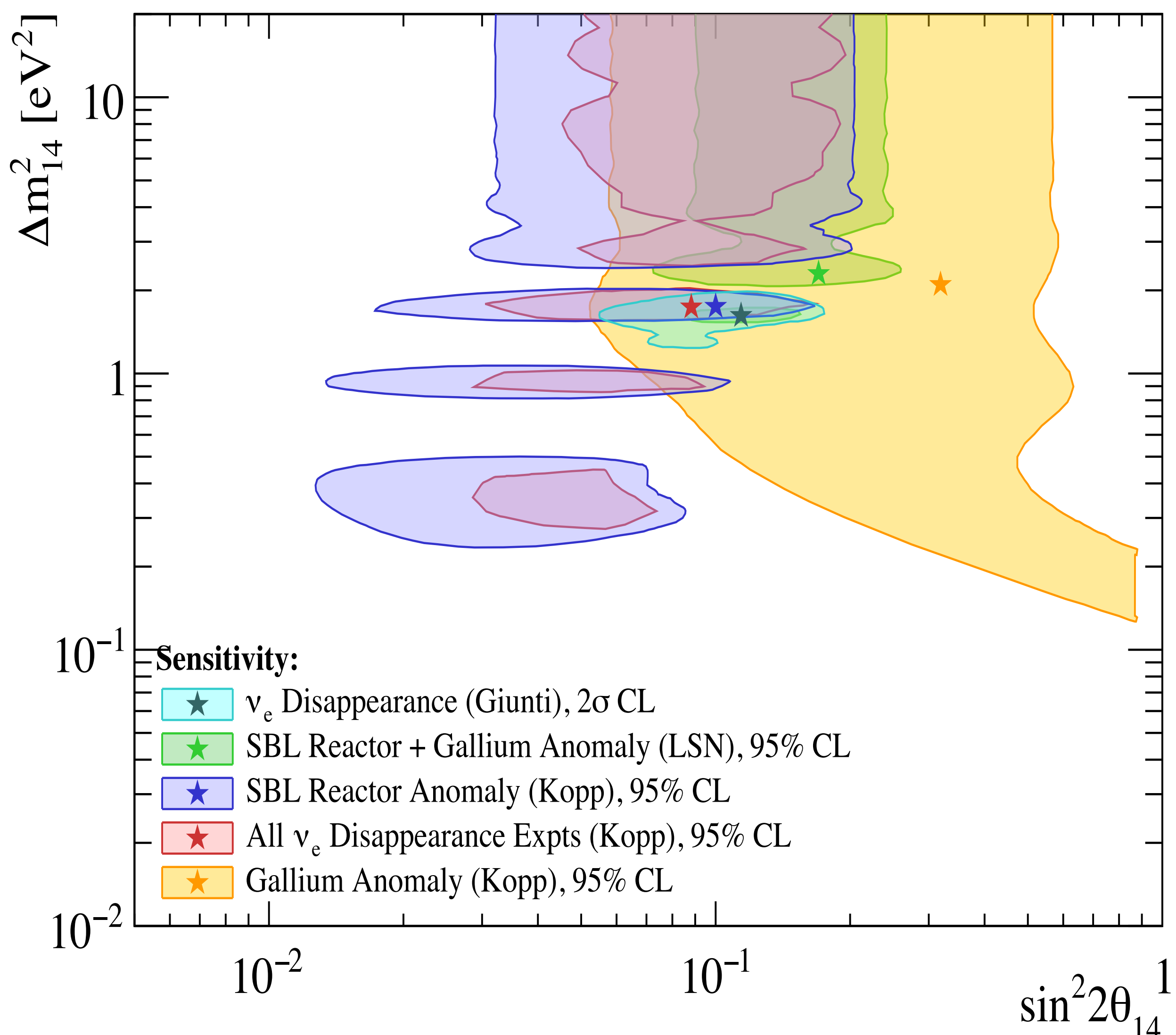
Daya Bay Ch Phys C41(2017)013002





Sterile Neutrino Interpretation

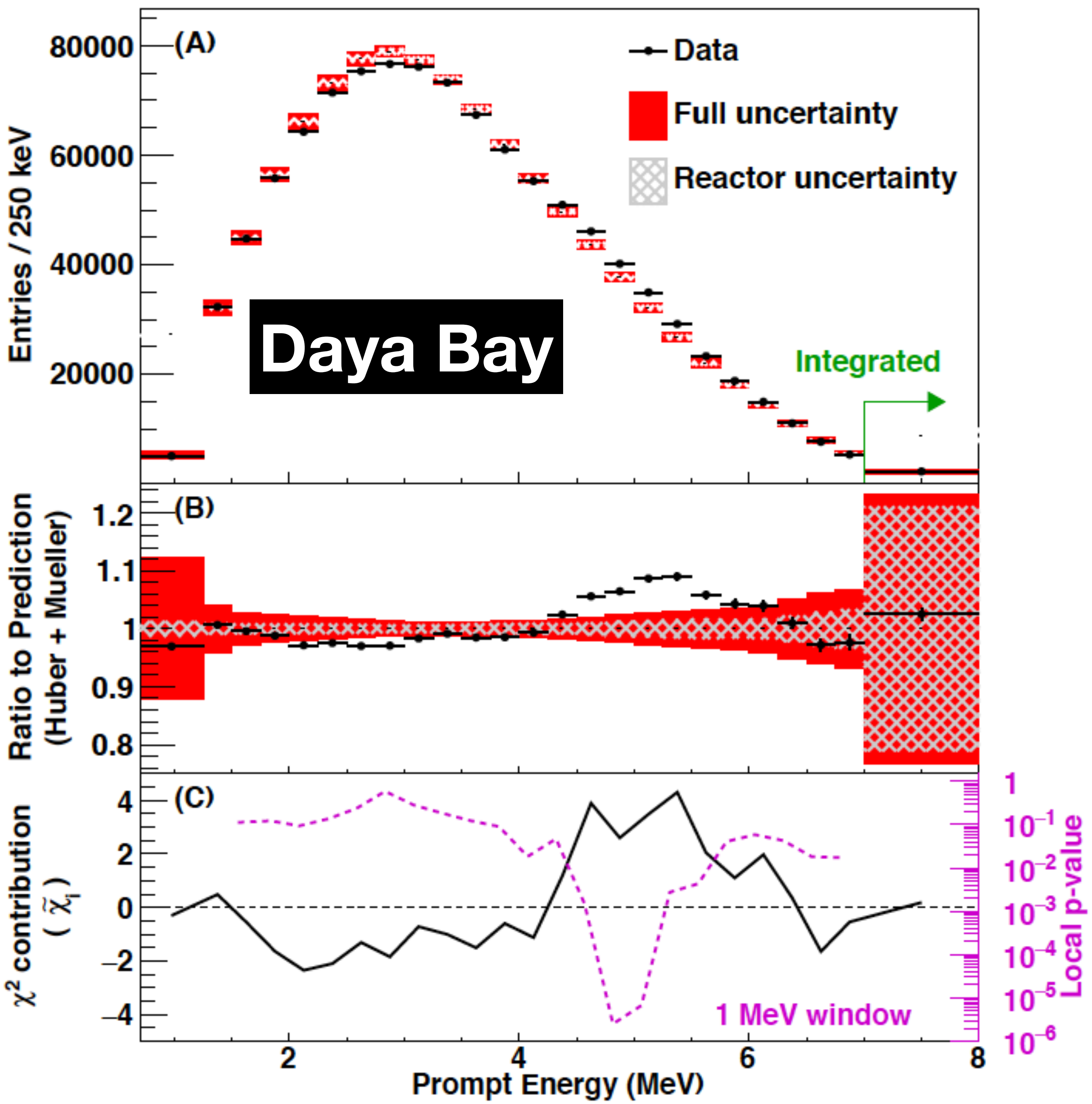
"The PROSPECT Physics Program"
J.Phys. G43 (2016) no.11, 113001

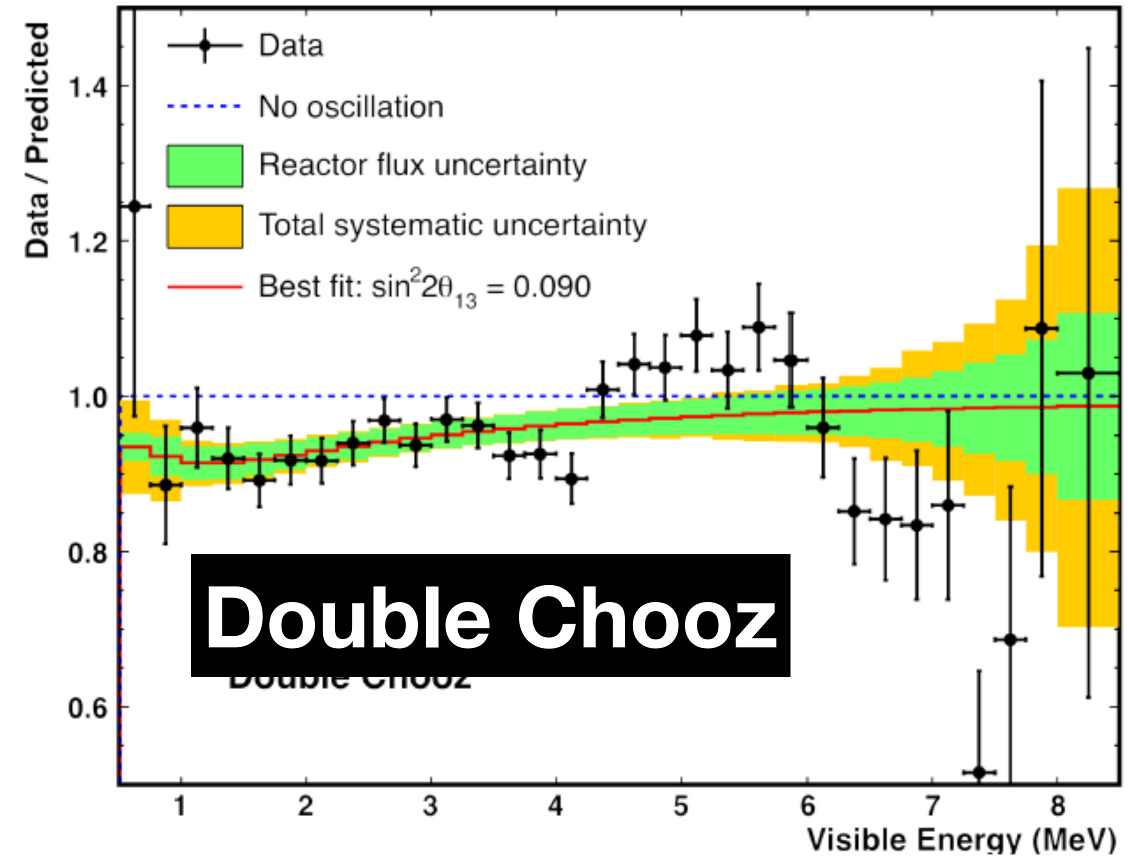


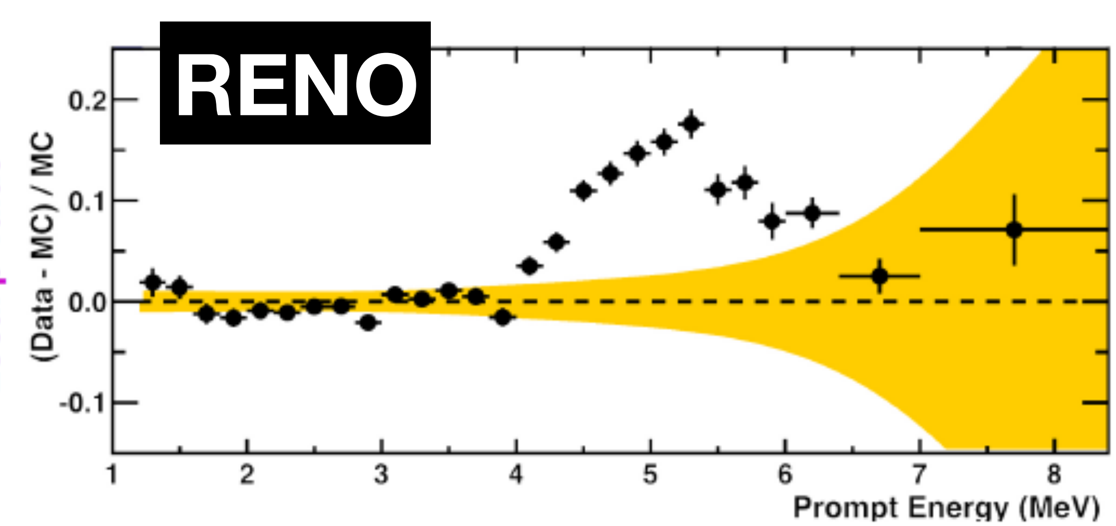
Implied oscillation length
on the order of meters!

The 5 MeV "Bump"

Something is odd near 5 MeV of prompt energy

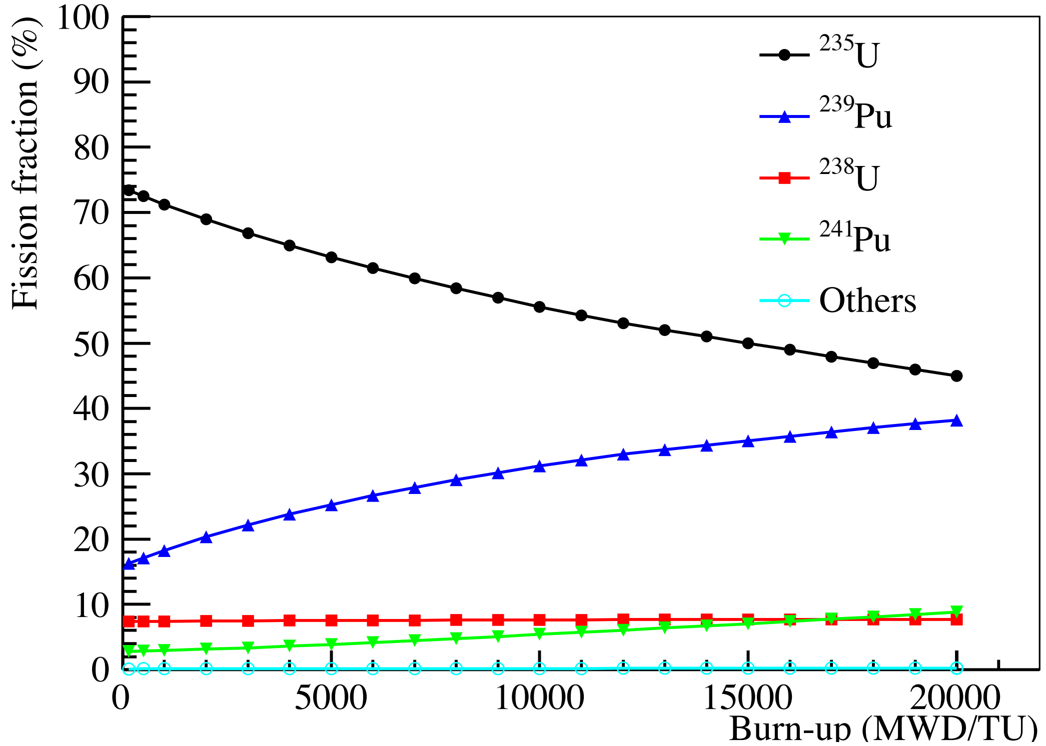


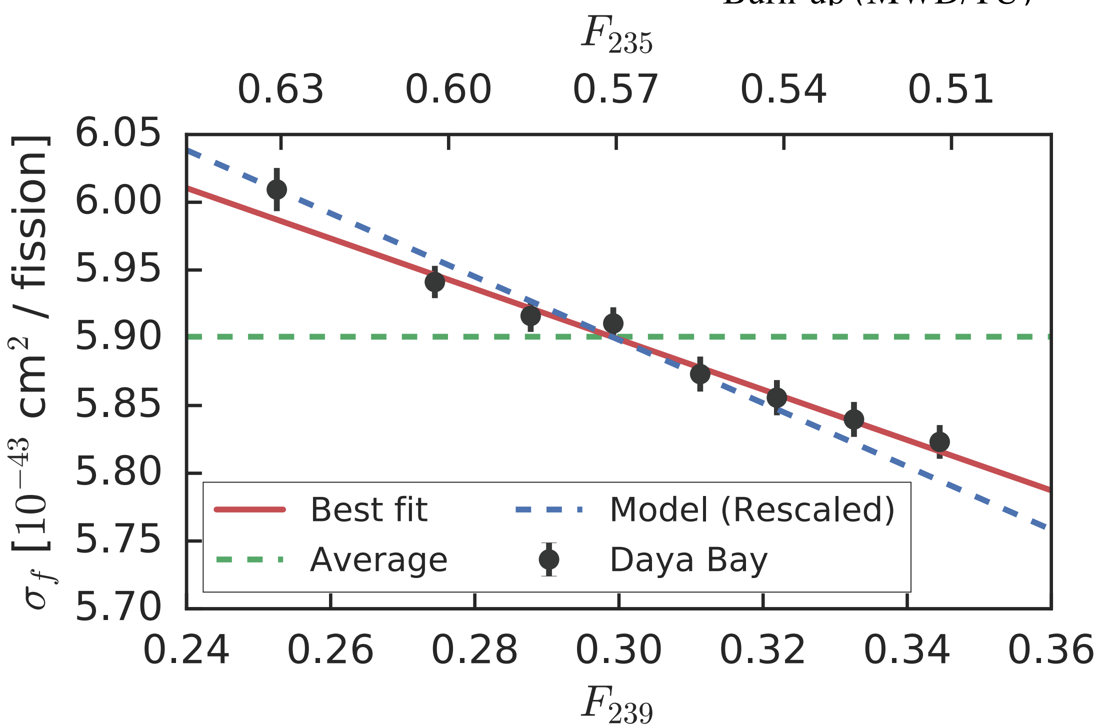


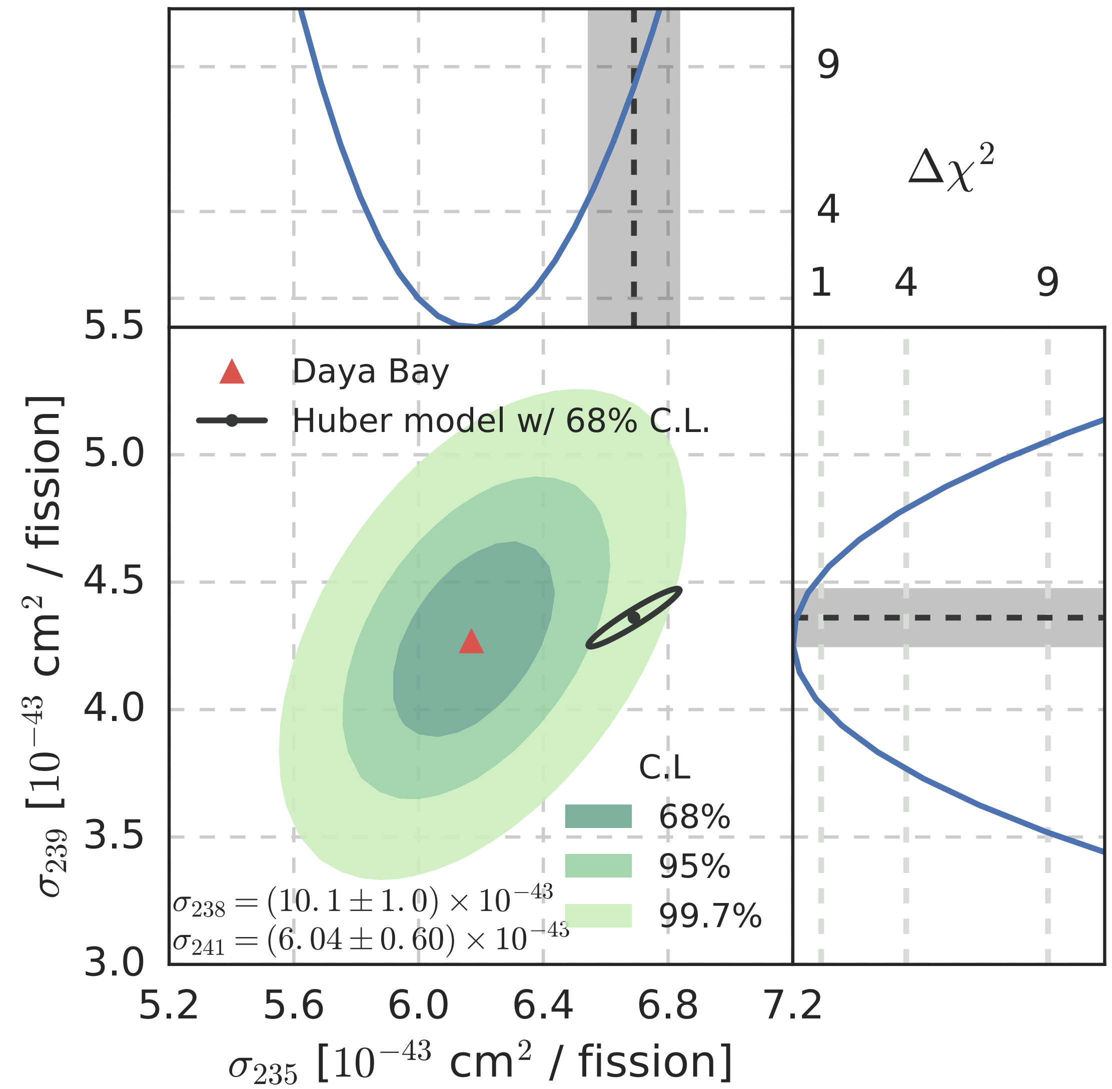


Caveat: Fuel Evolution

Daya Bay, Phys.Rev.Lett. 118 (2017) 251801







➥ *Something odd with ^{235}U flux contribution calculation?*

Brand New: arXiv:1806.00574

PROSPECT

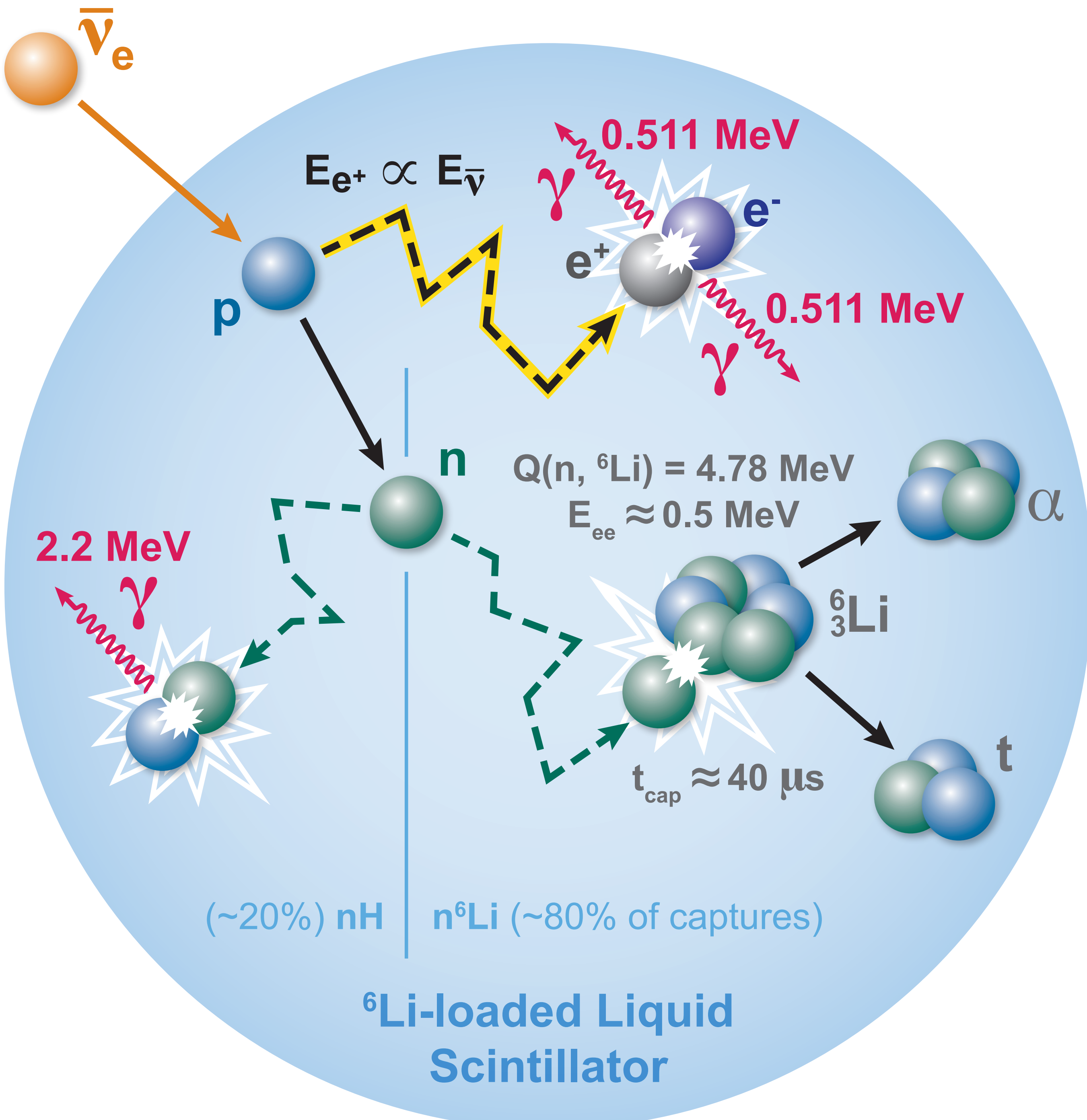
The PROSPECT Physics Program, J. Ashenfelter, et al., J.Phys. G43 (2016)

See also detailed paper on 50 liter prototype detector, arXiv:1805.09245

- Two primary goals:
  1. A search for sterile neutrinos with $\Delta m^2 \approx 1 eV^2$ through the disappearance of reactor electron antineutrinos
  2. Precision measurement of the prompt energy spectrum of neutrinos from a highly enriched ^{235}U reactor core

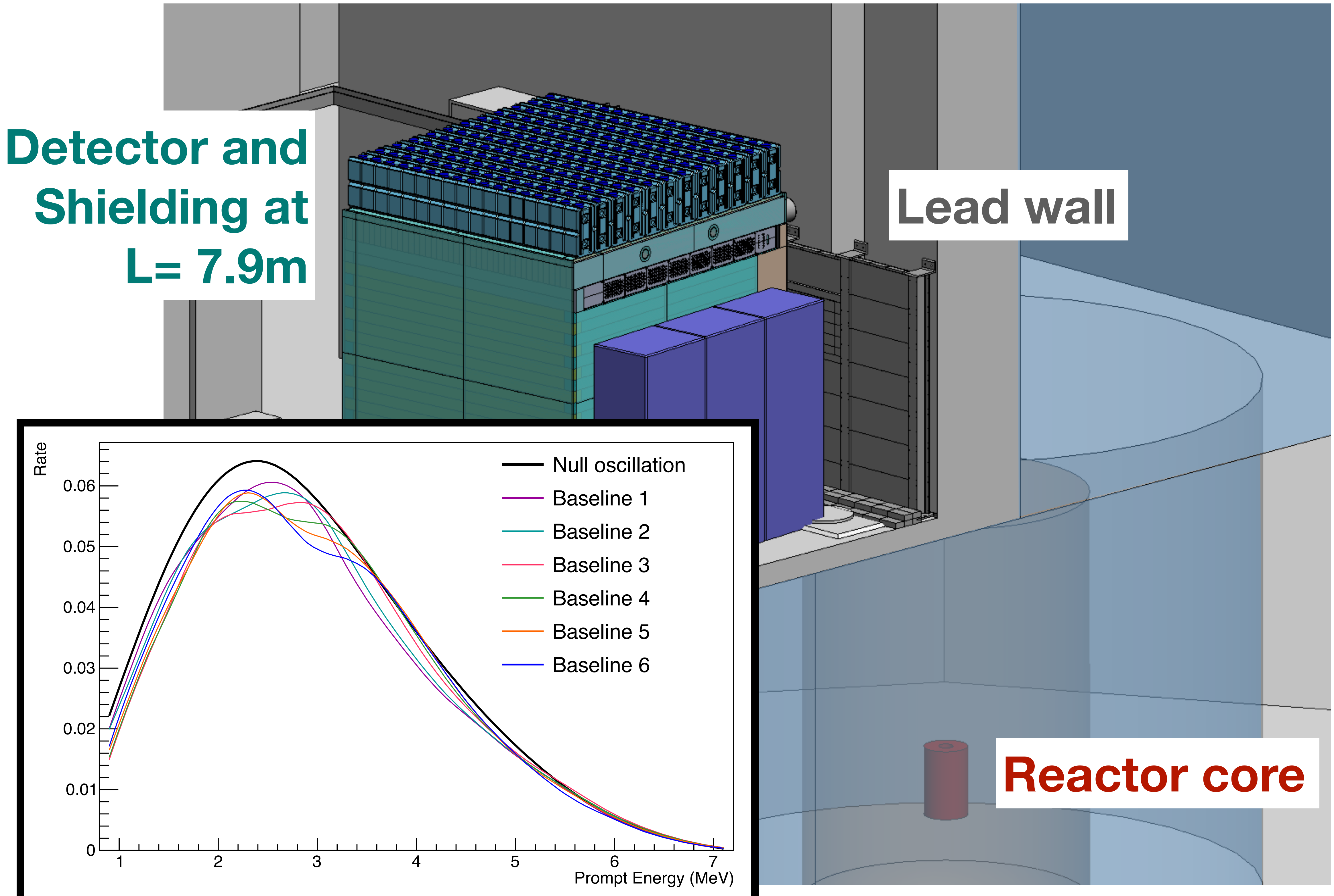
- Essential features:
  - Highly segmented detector to measure spectrum dependence on baseline and to combat backgrounds
  - Uses ^6Li for localized neutron capture signal
  - Neutrinos from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory

PROSPECT: $\bar{\nu}_e$ Detection

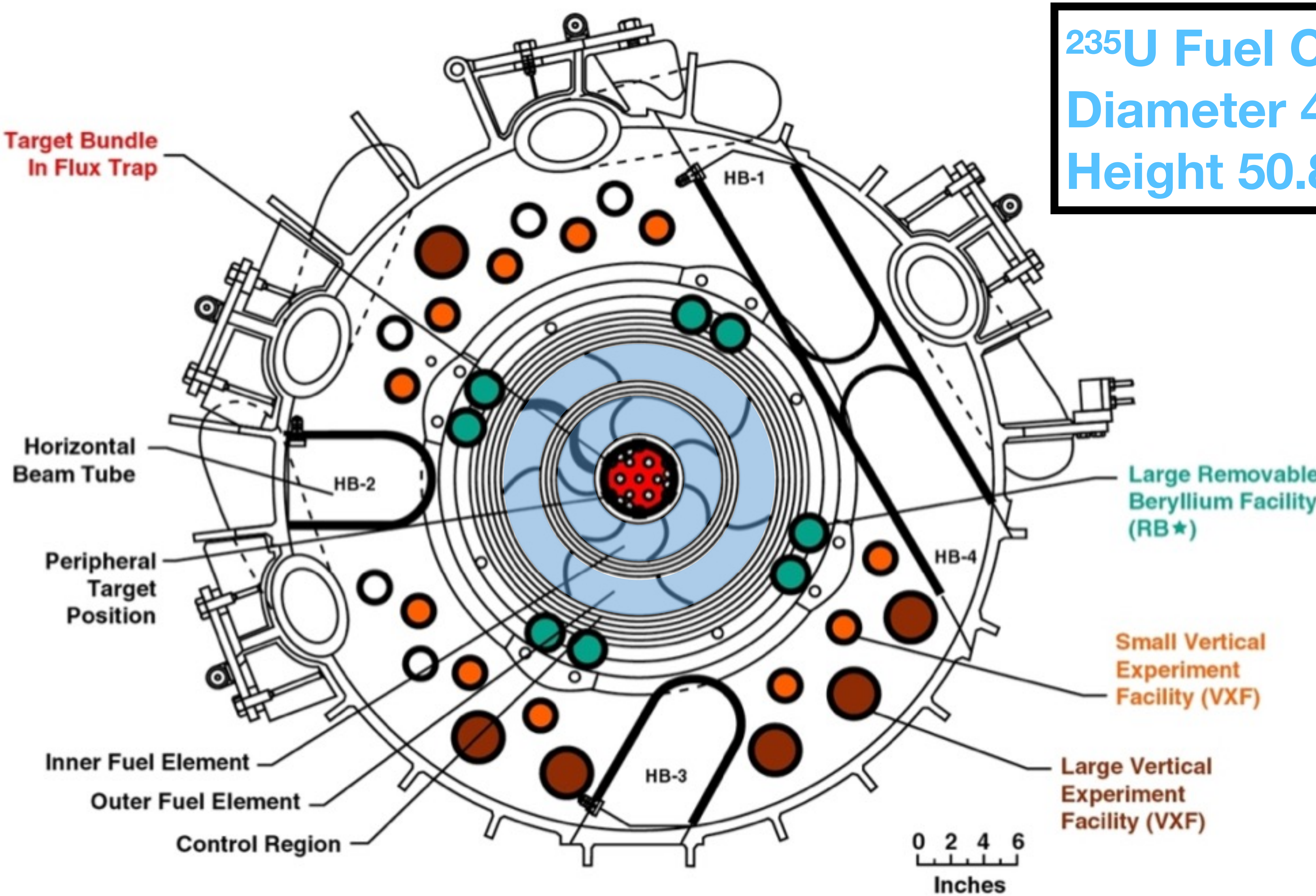


- Prompt energy gives neutrino energy, and includes annihilation gamma rays.
- Neutron capture on ^{6}Li localizes signal.
- Light from delayed signal is quenched, but pulse shape discrimination works.
- Some contributions from np capture.

Experiment Layout



HFIR Reactor Core

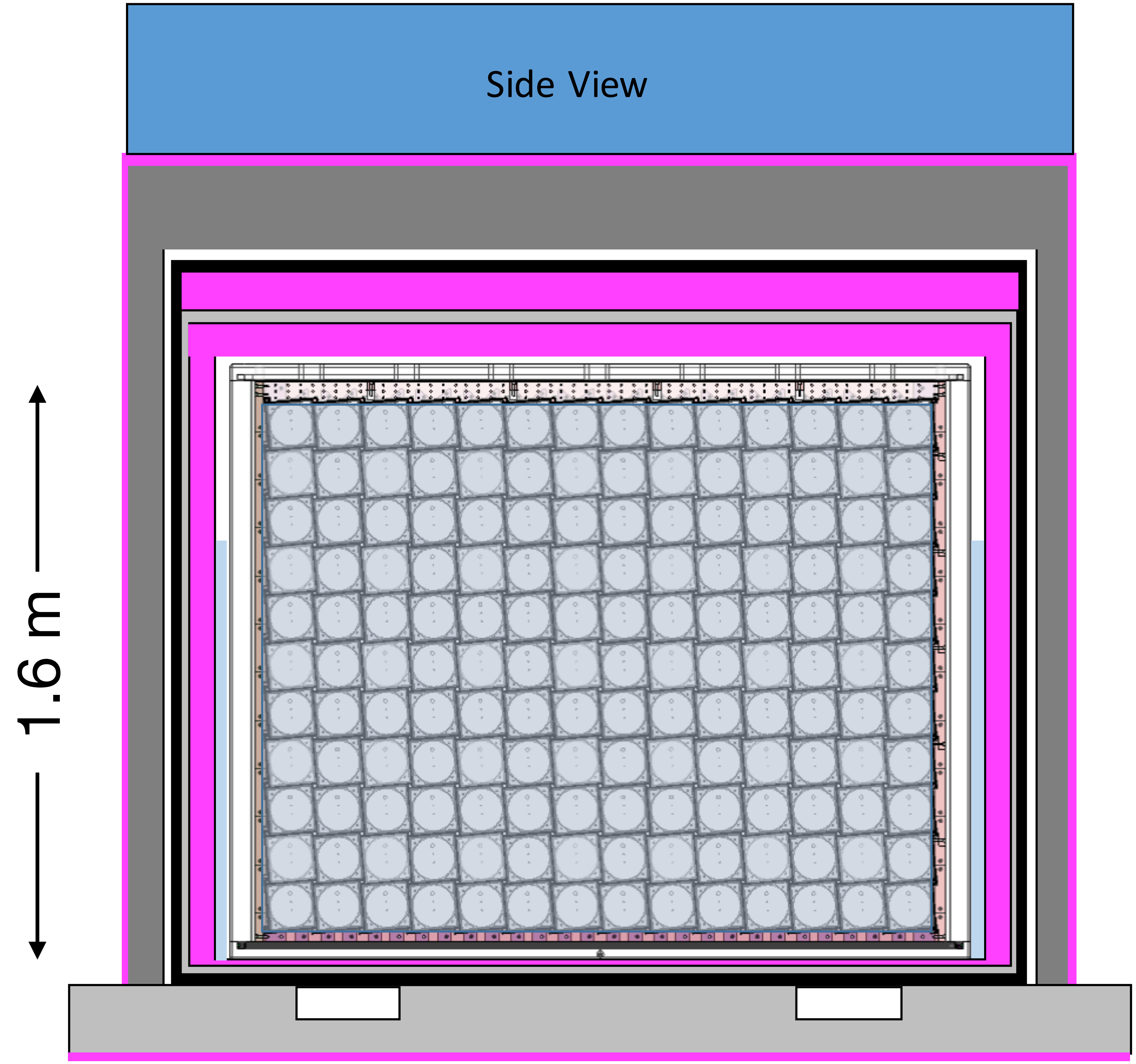


^{235}U Fuel Core:
Diameter 43.5 cm
Height 50.8 cm

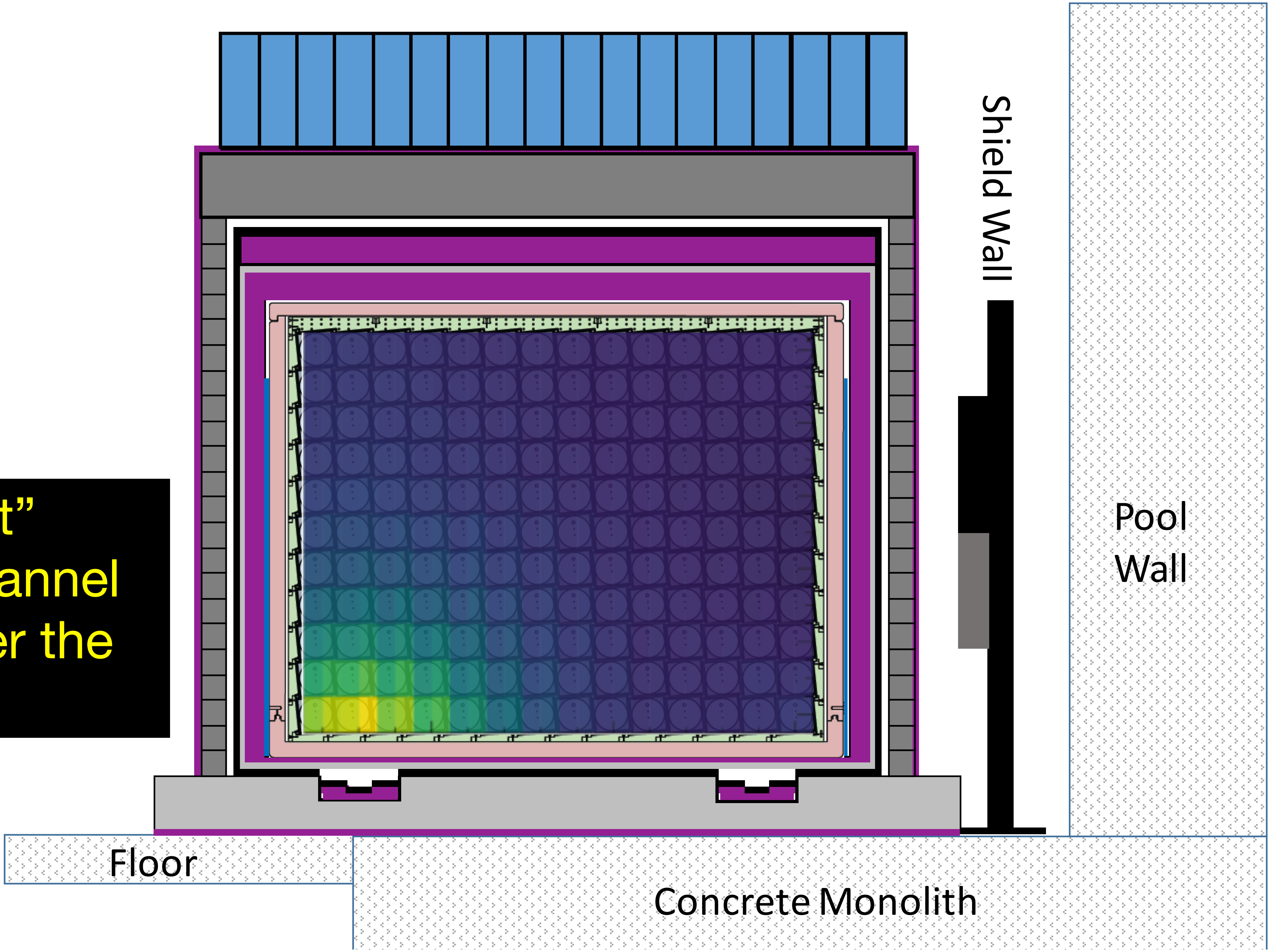
Detector Cross Section

Total of 11×14=154 detector modules

- Water Bricks
- Active volume
- PMTs
- Acrylic tank
- Water
- Al tank
- Lead
- Poly
- Borated poly
- Chassis

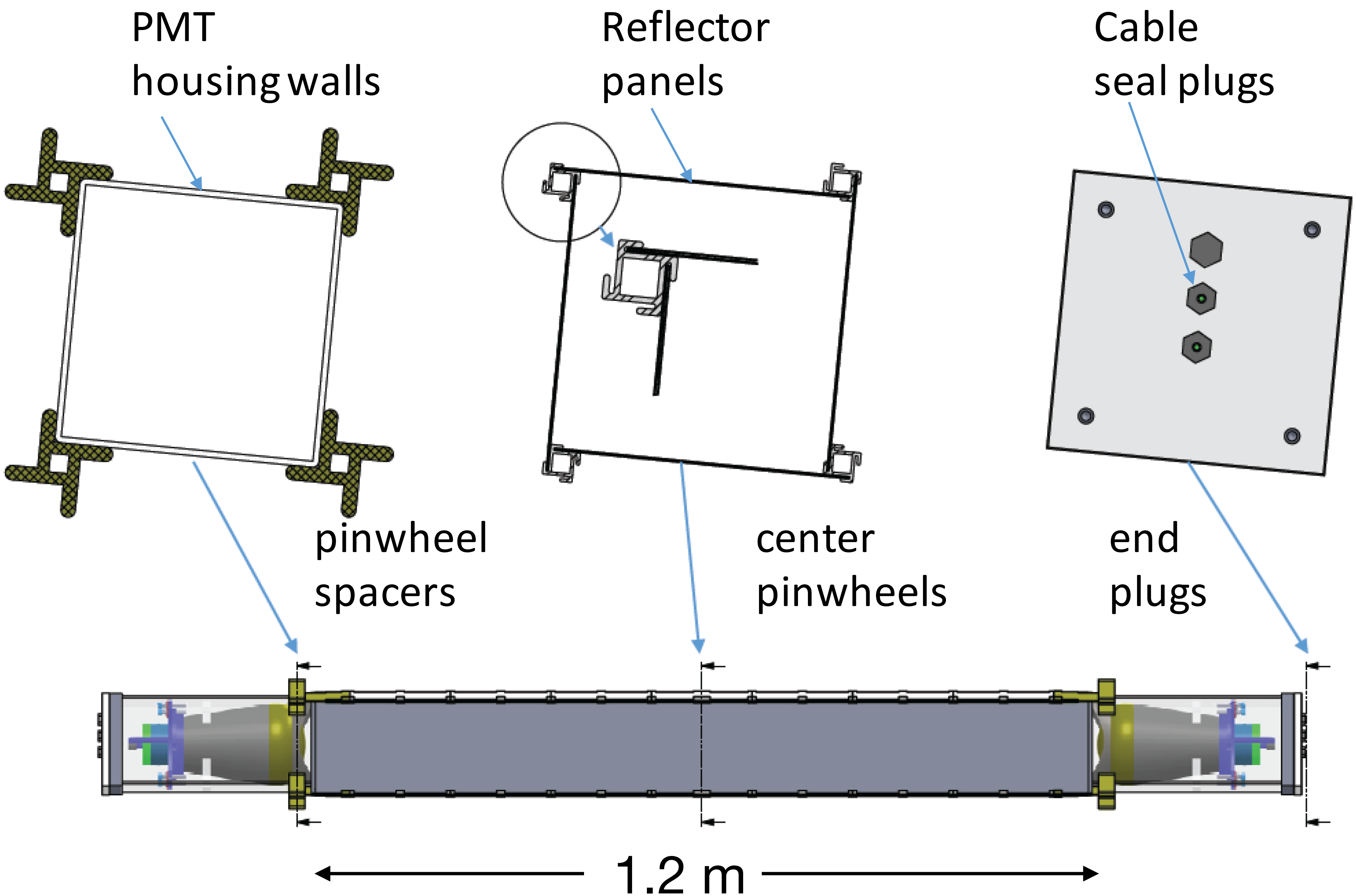


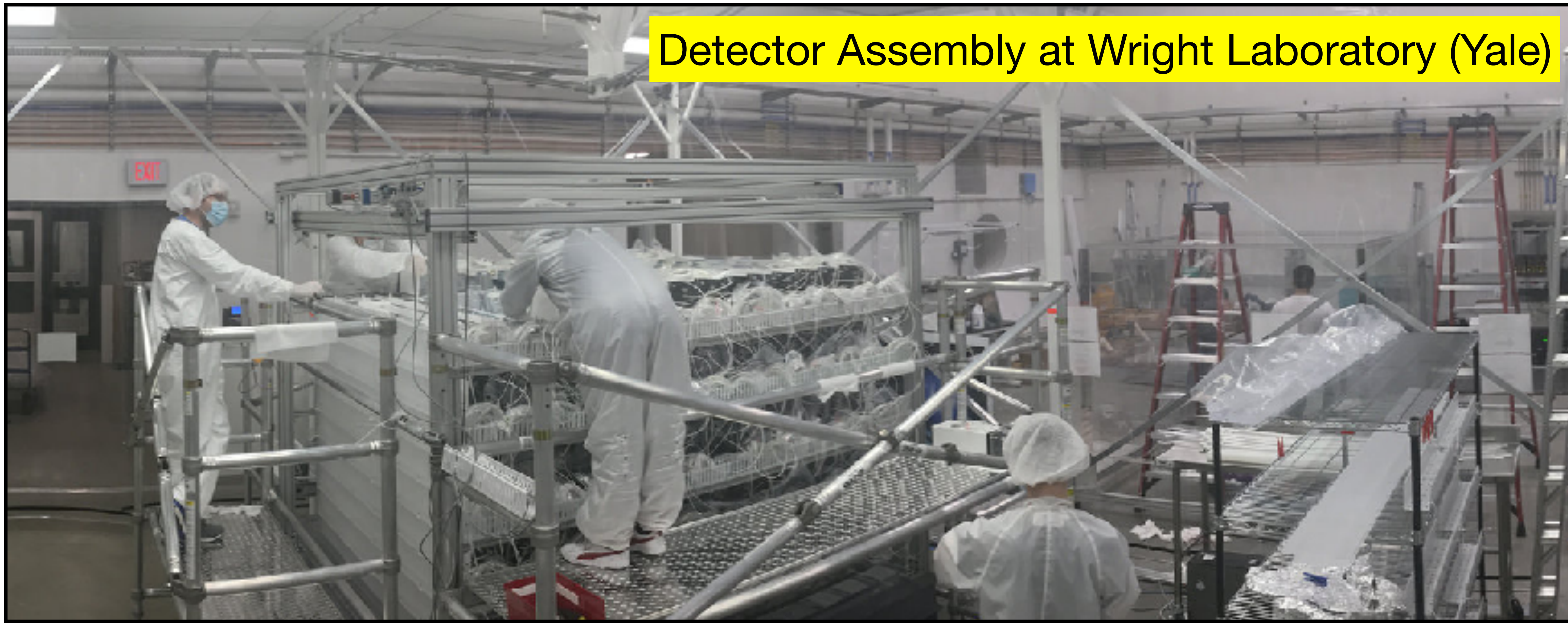
Reactor Shielding

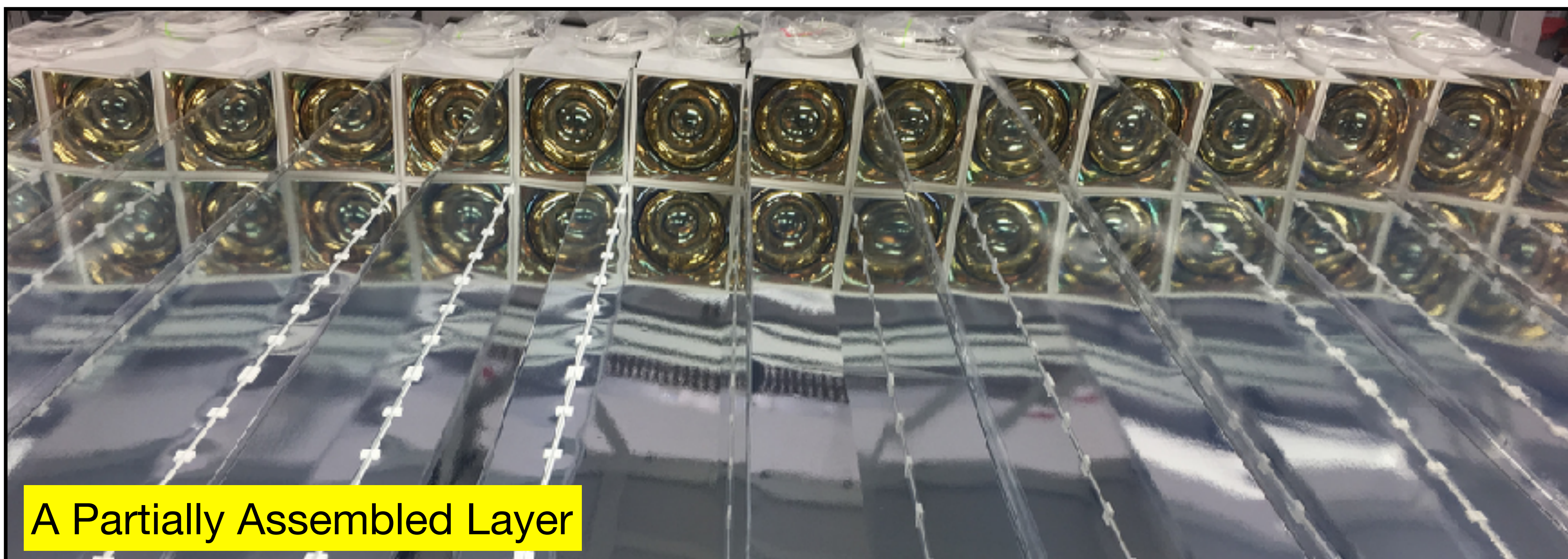


"Hot Spot" where channel is not over the monolith.

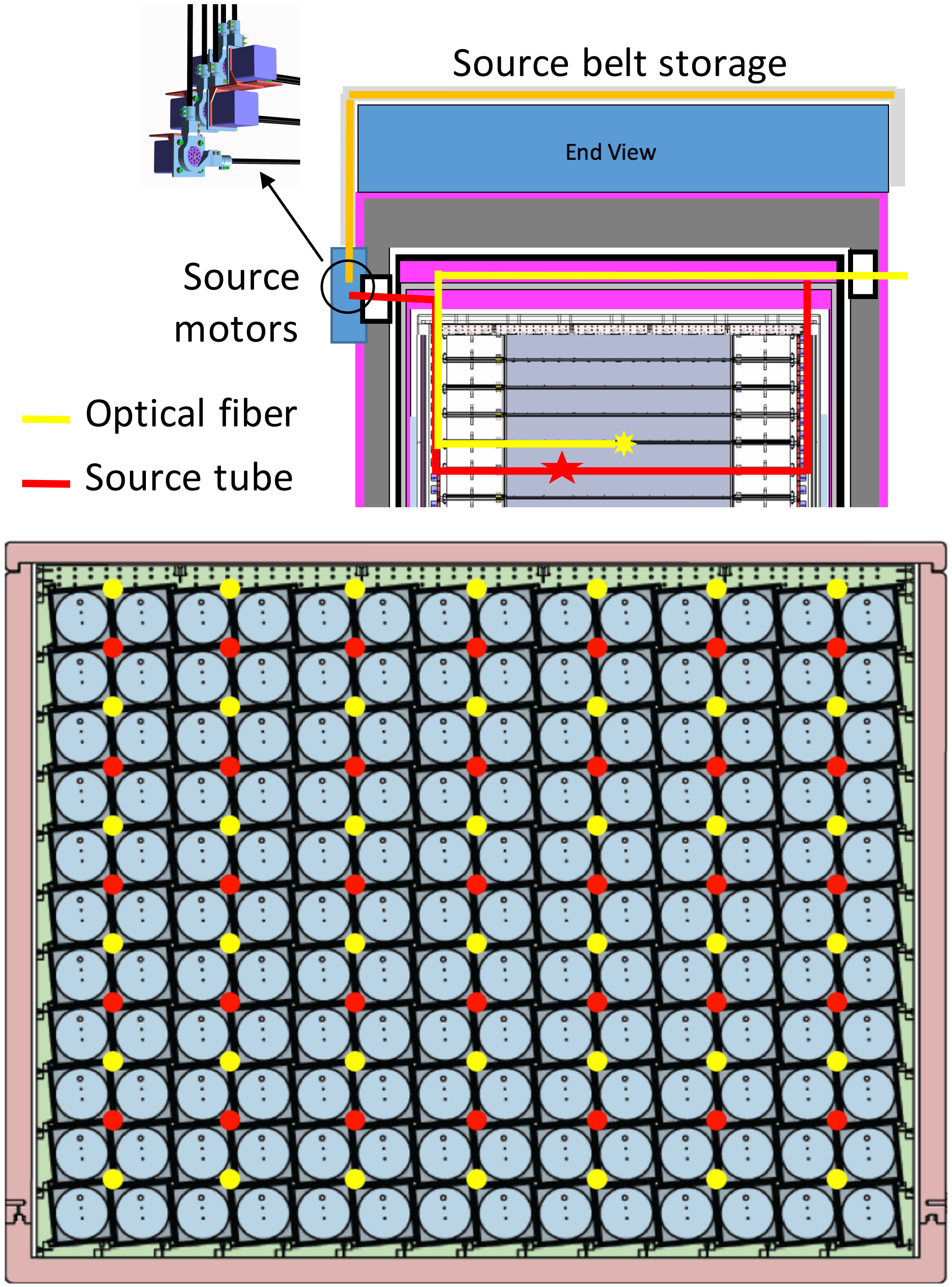
Single Detector Module




Detector Assembly at Wright Laboratory (Yale)
EXIT

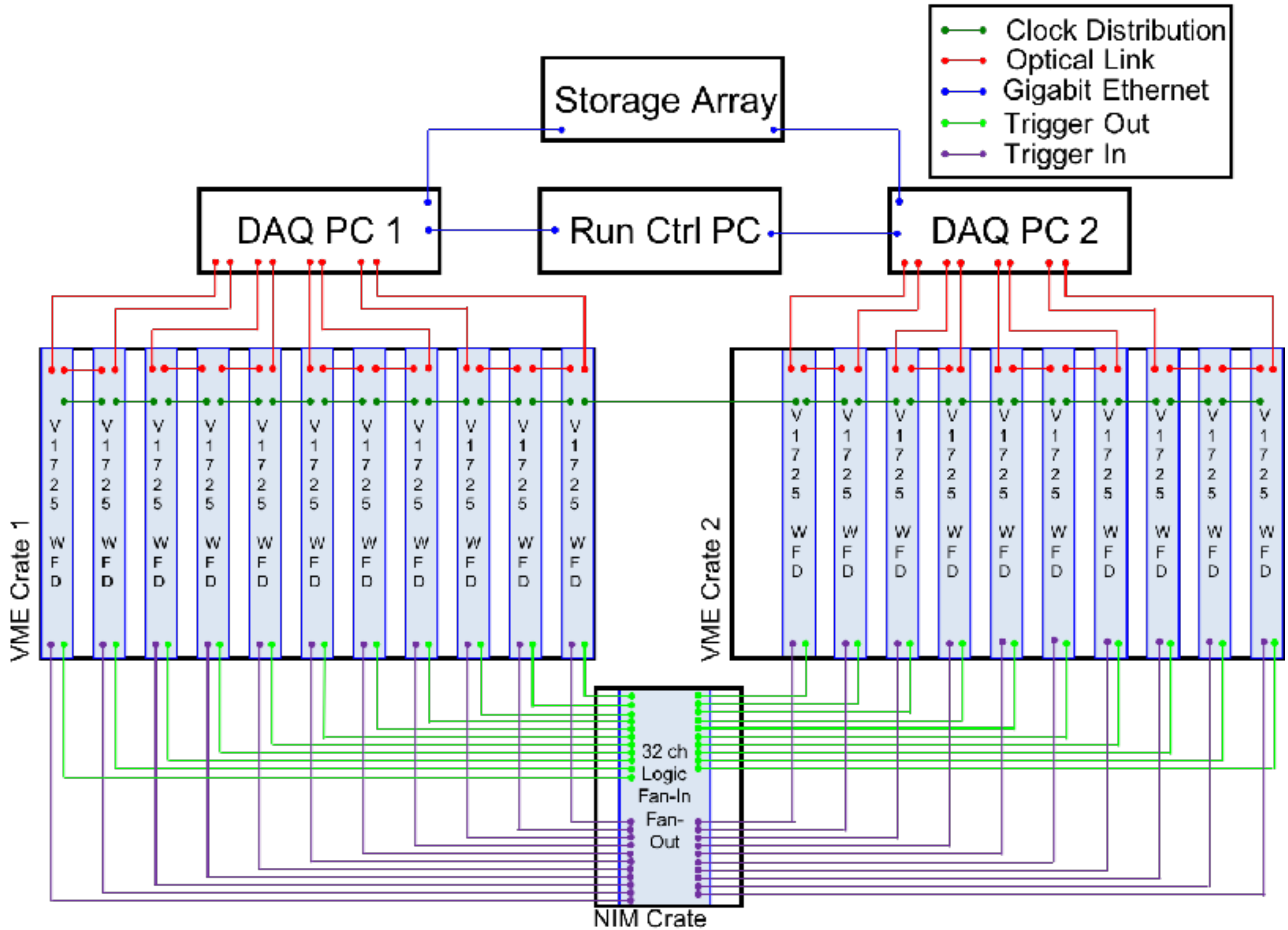

A Partially Assembled Layer

Calibration Systems



- Optical fibers driven by a 450 nm pulsed laser for timing, single PE's
- Radioactive sources (^{22}Na, ^{60}Co, ^{137}Cs for $\beta^{\pm}$, γ; ^{252}Cf for neutrons) insertable/removable on belts inside tubes
- Inherent radioactivity from ambient radon and ^{227}Ac scintillator "spike"

Data Acquisition



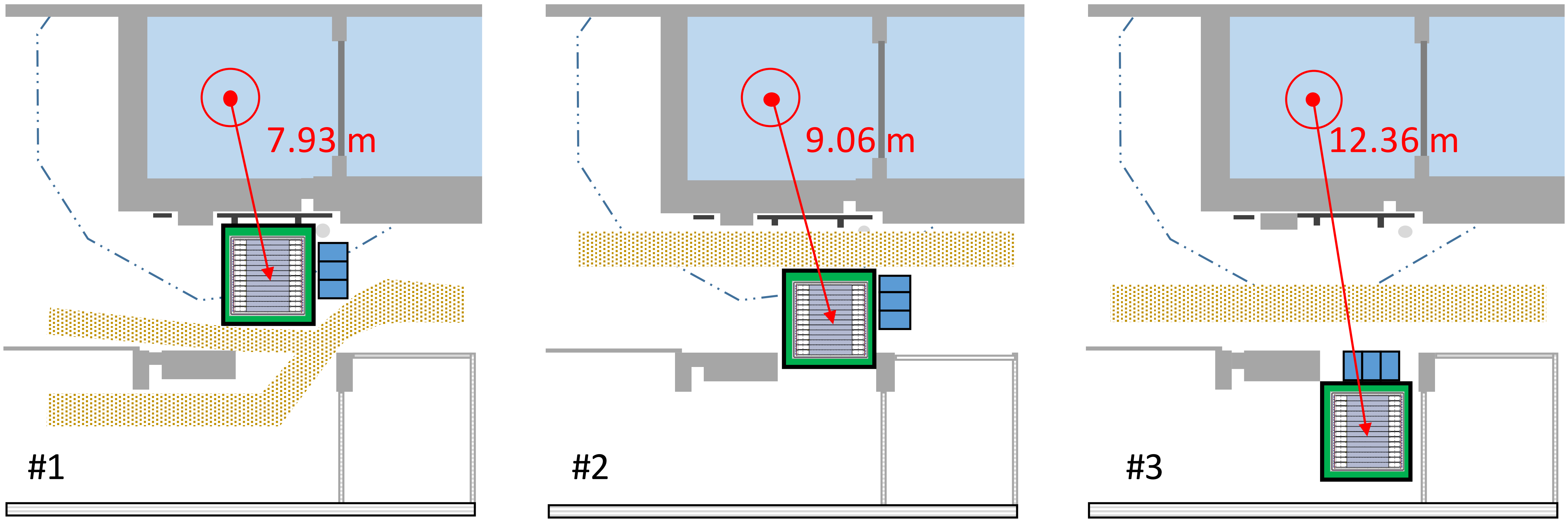
Data Rates and Volume

Quantity/Run Condition	Reactor On	Reactor Off	Calibration
Acquisition Event Rate (kHz)	28	4	35
Segment Event Rate (kHz)	115	35	190
Avg. Segment Multiplicity	4.0	7.0	5.5
Max Opt. Link Rate (MB/s)	3.0	1.0	7.2
Min Opt. Link Rate (MB/s)	1.1	0.6	2.2
Data Volume per Day (GB)	671	312	476

Processing Step/Run Condition	RxOn	RxOff	Calibration
Raw File Size (GB/run)	29	13	22
Unpacked File Size (GB/run)	30	13	23
Raw → Unpack processing time (CPU-min/file)	98	44	77
DetPulse File Size (GB/run)	8.2	3.7	4.9
Unpack → DetPulse processing time (CPU-min/file)	58	26	37
PhysPulse File Size (GB/run)	3.2	1.4	2.4
DetPulse → PhysPulse processing time (CPU-min/file)	14	6.2	8.7

Possible Baselines

The detector is on a movable platform



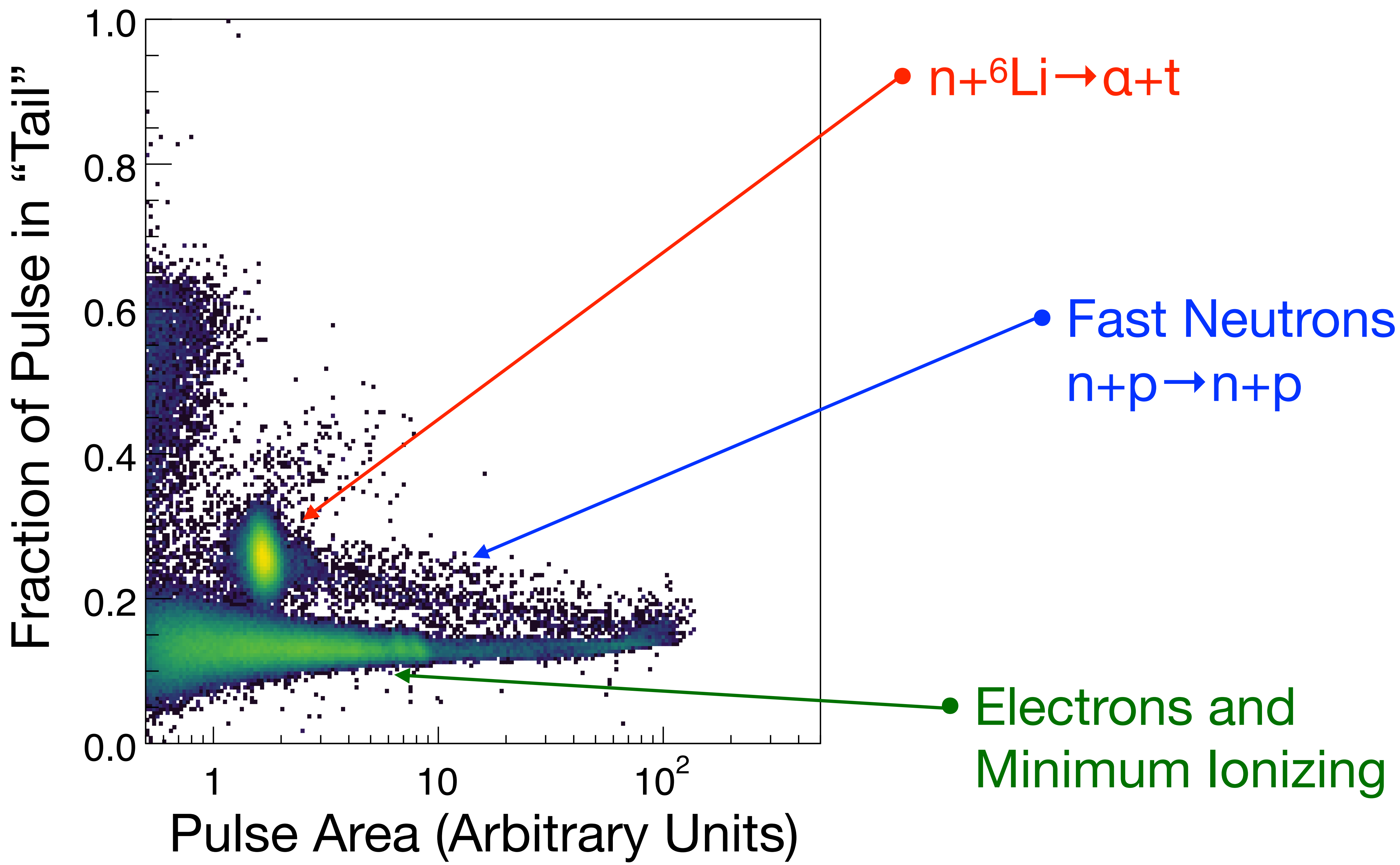
Current position

Movement must respect existing walls and allow for standard walkway access, maintaining detector orientation, but can allow the electronics racks to be relocated.

Performance & Analysis

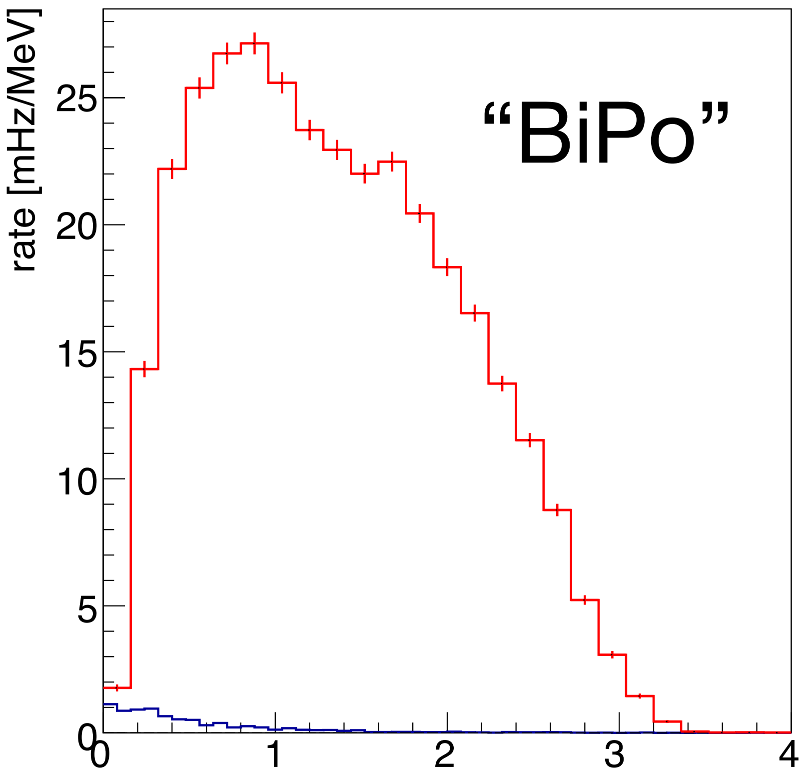
All Results Preliminary

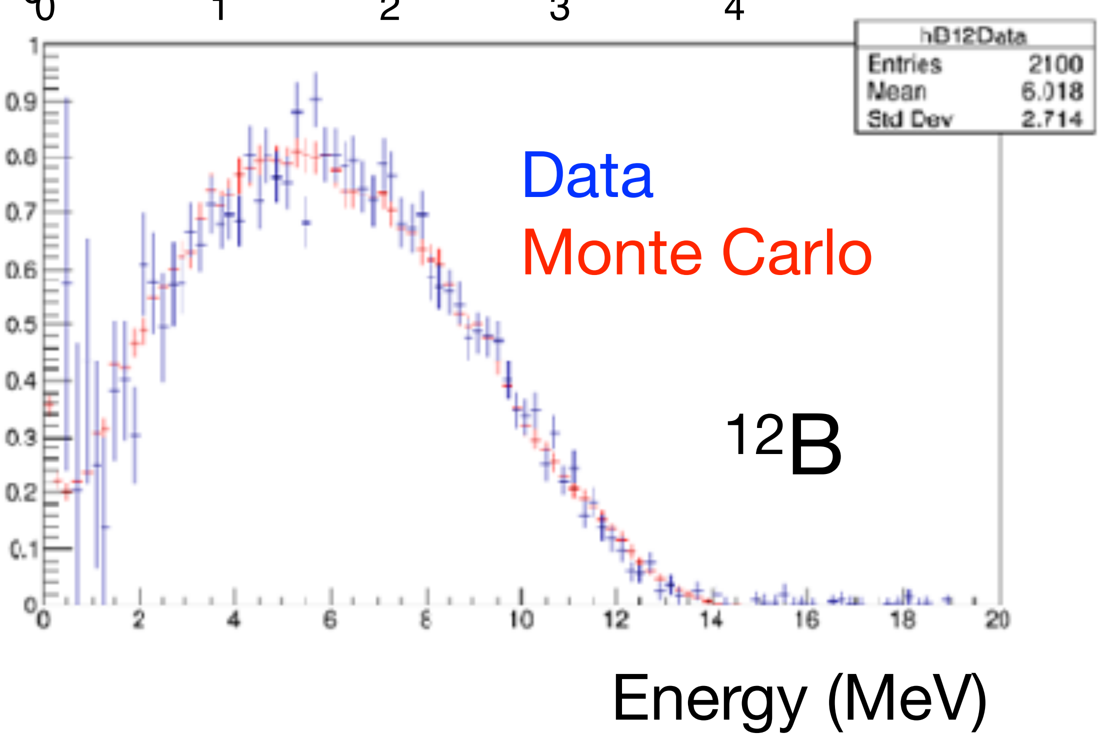
Pulse Shape Discrimination



Calibrations

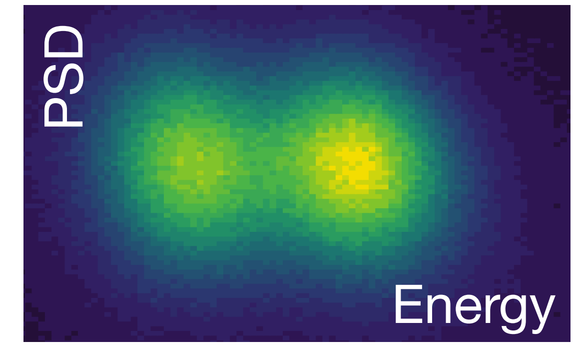
Energy

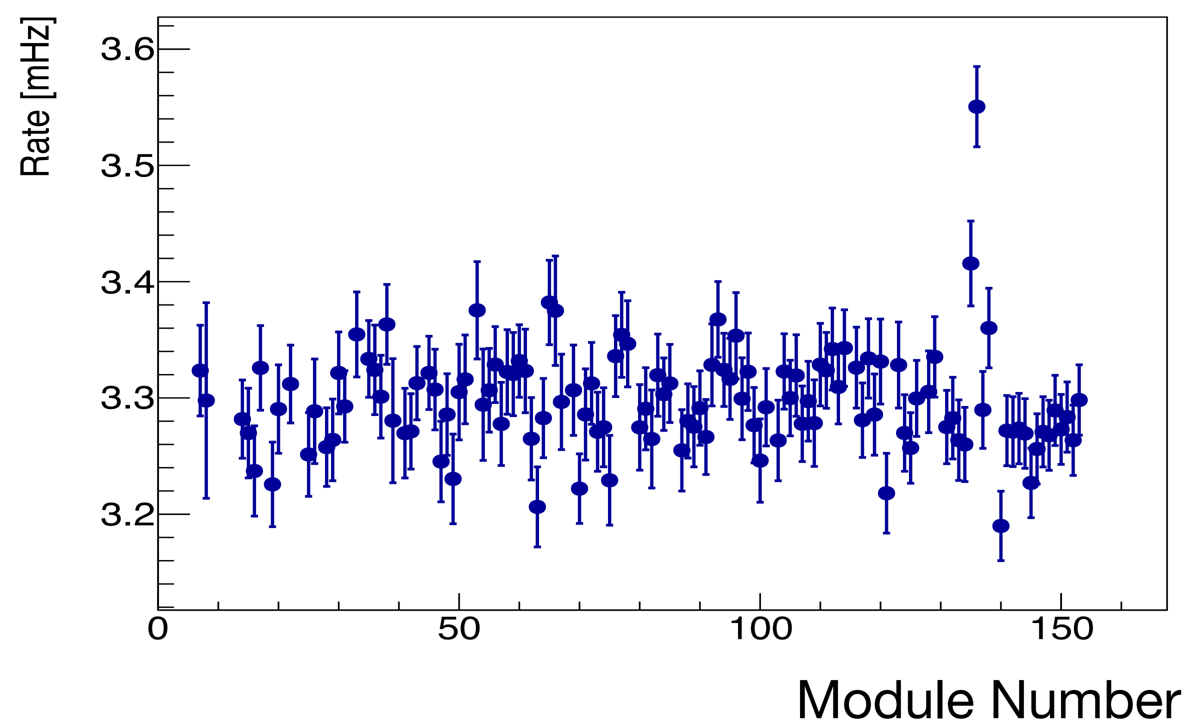




Volume × Efficiency

^{227}Ac: Two α's, same PSD, but different energy

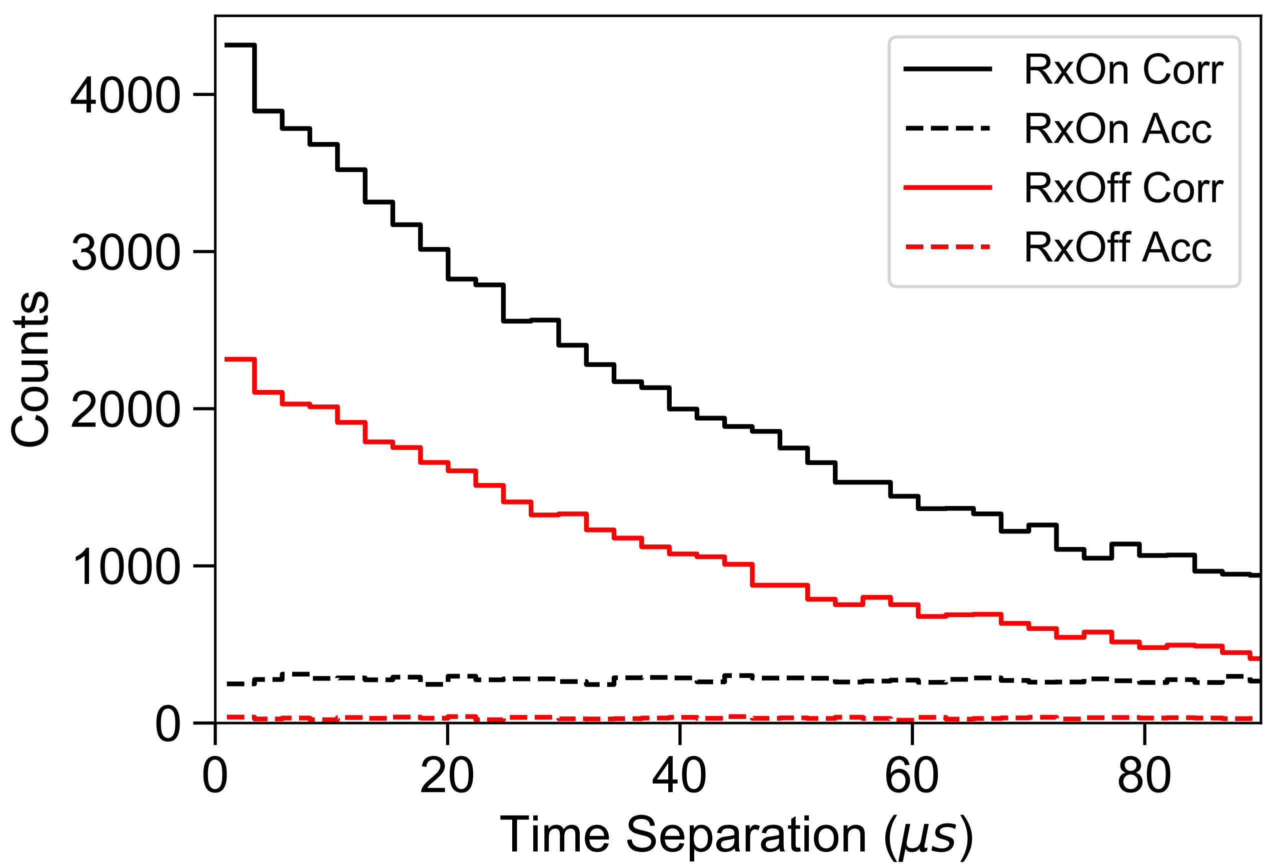




Measured with ^{227}Ac Spike: Double α-decay with 0.5 Bq dissolved AcCl in scintillator

Signal and Background

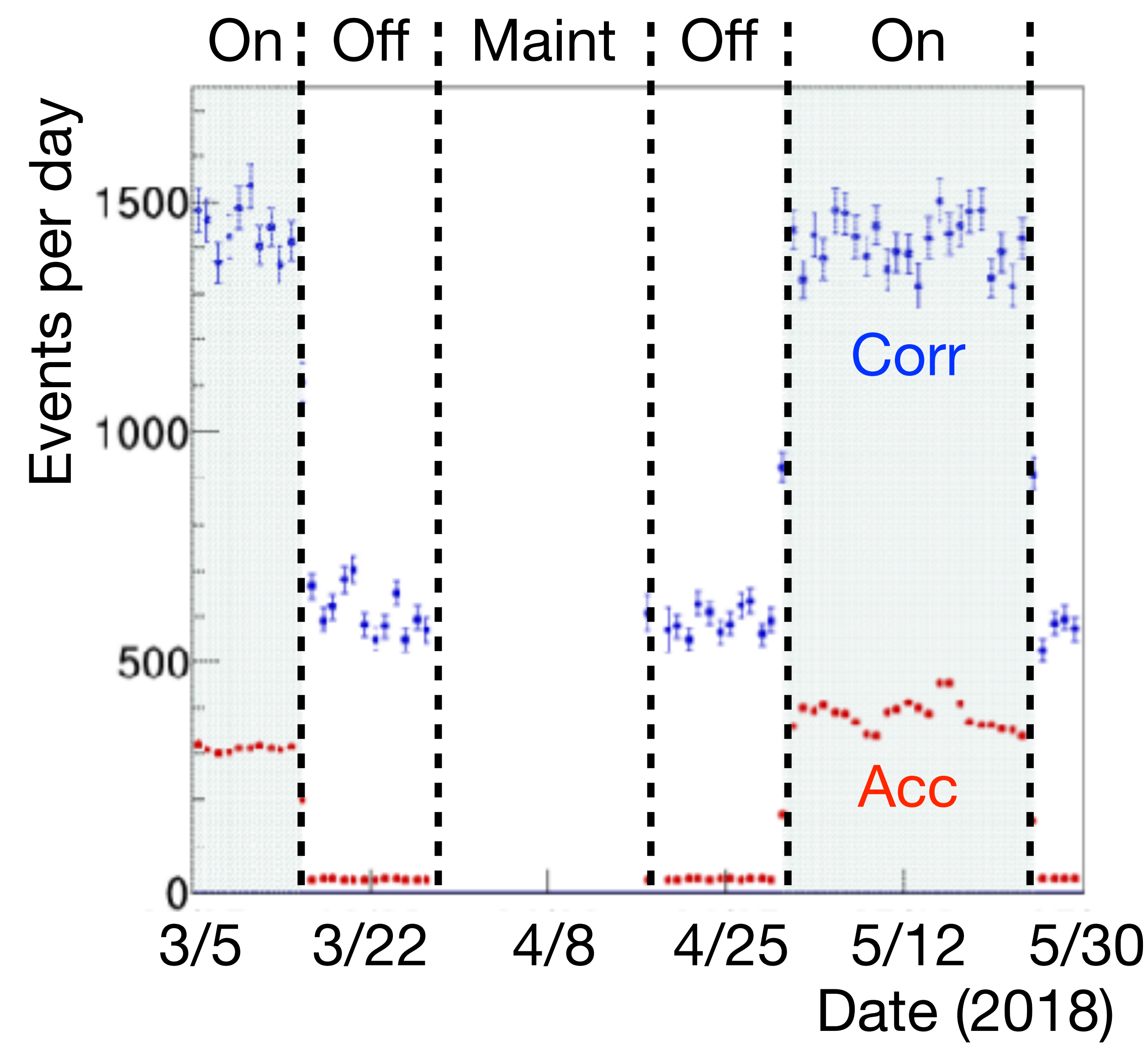
Correlated vs Accidental



Identify α+t, then…

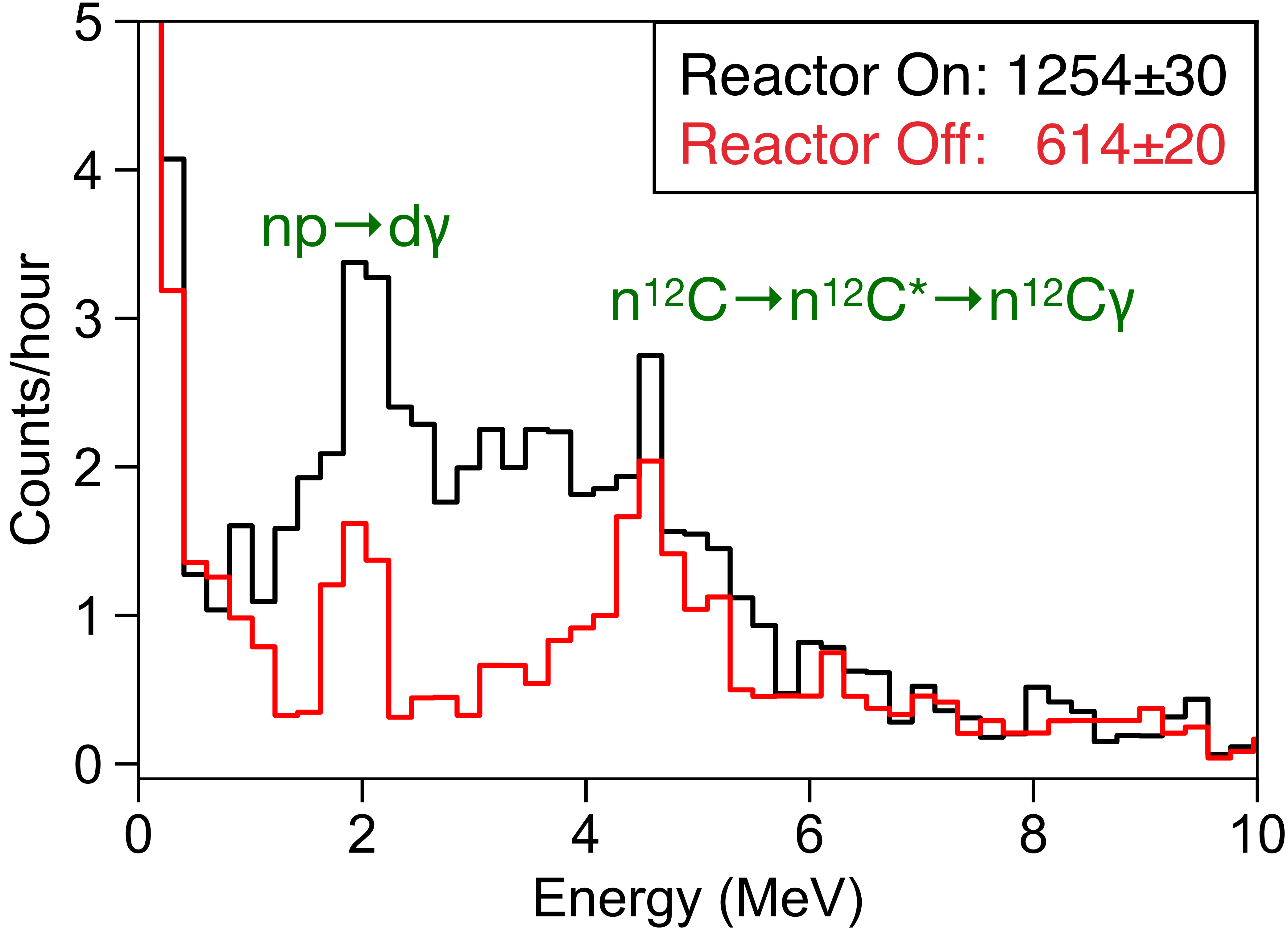
<u>Corr</u>: Look for IBD μs before

<u>Acc</u>: Look for IBD ms after



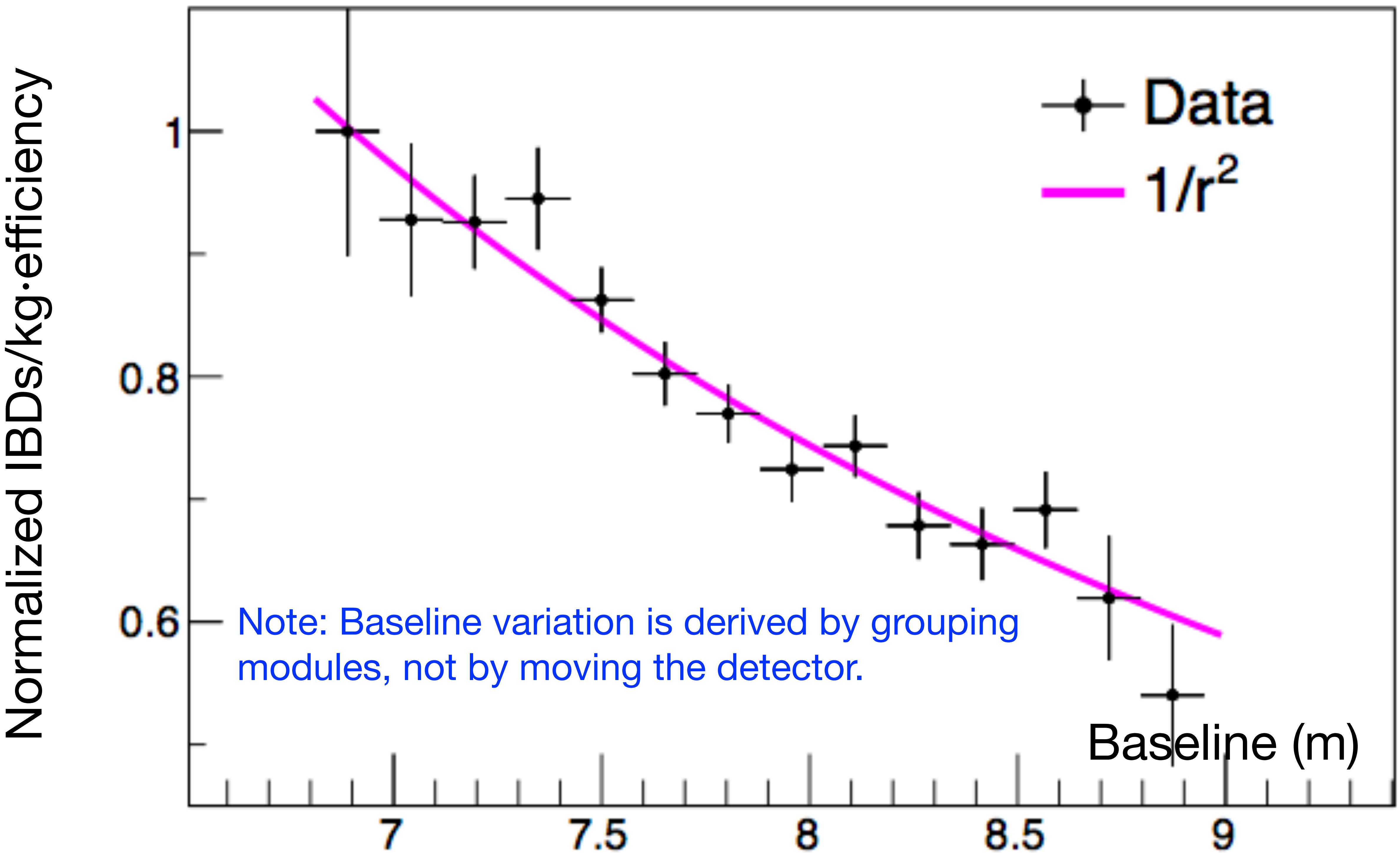
Now subtract accidental from correlated, and examine the prompt energy spectrum…

24 Hours of Neutrinos



IBD Events vs Baseline

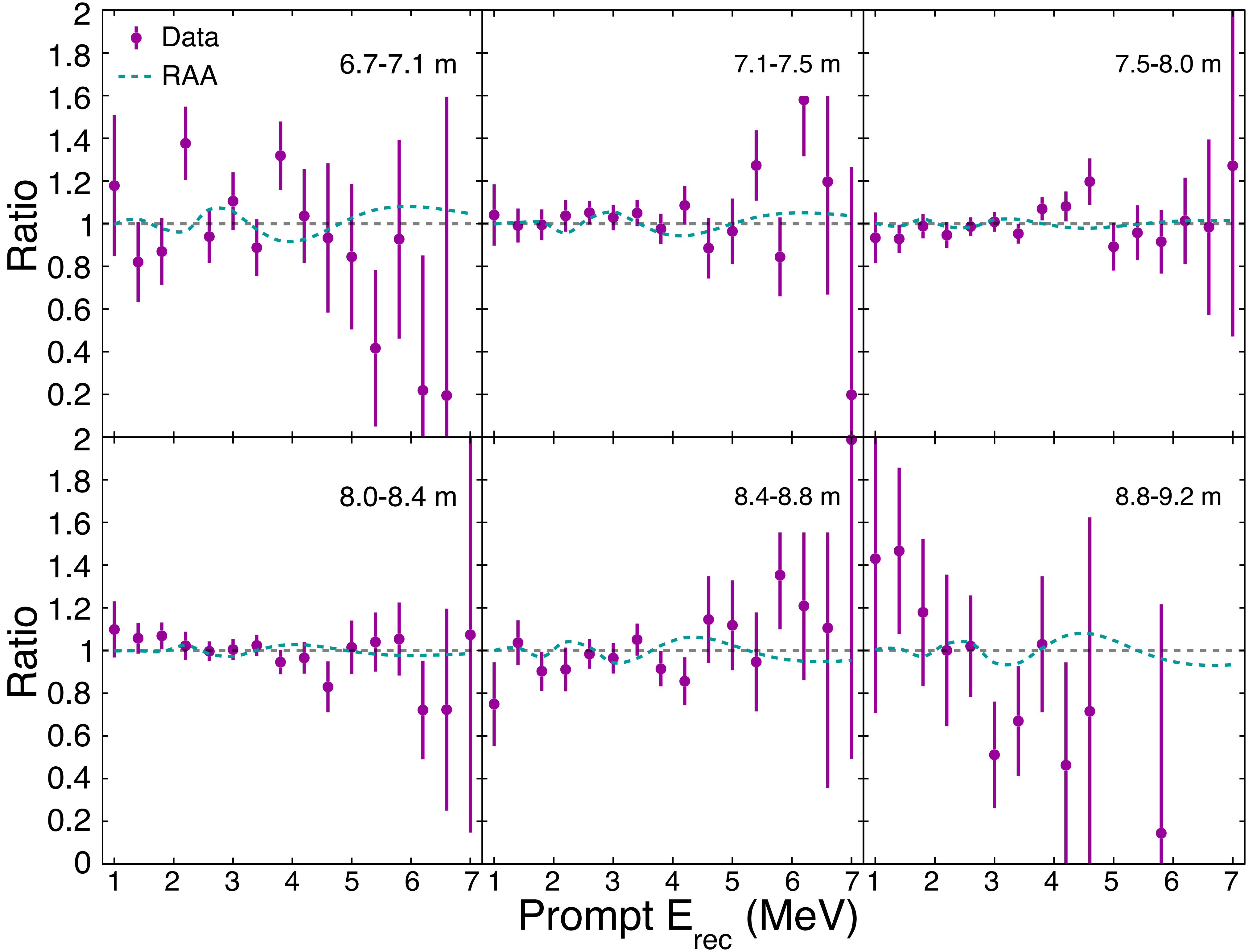
$N=\{N^{(On)}_{Corr} - N^{(On)}_{Acc}\} - \{N^{(Off)}_{Corr} - N^{(Off)}_{Acc}\}$



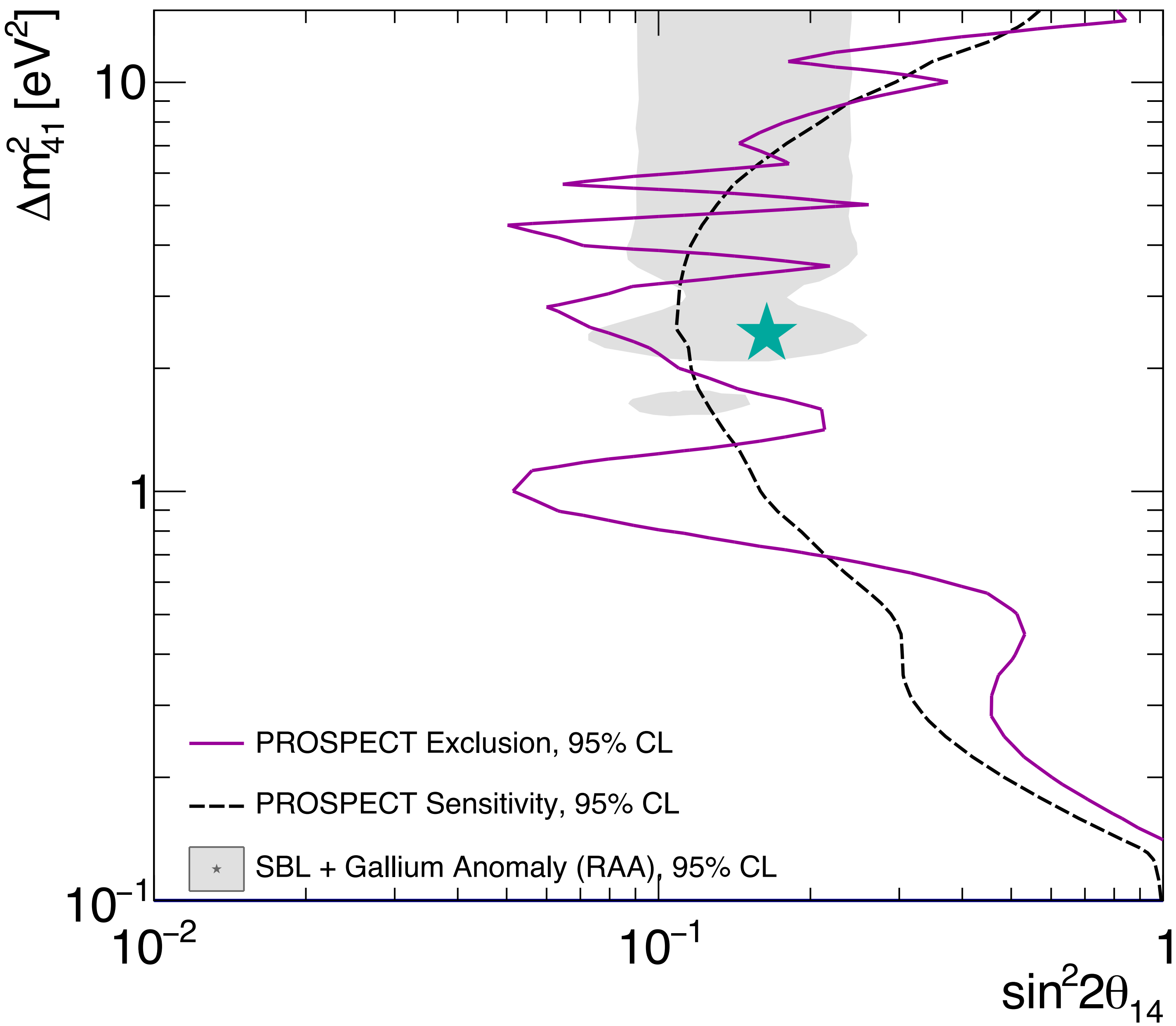
Note: Baseline variation is derived by grouping modules, not by moving the detector.

Spectrum Ratio vs Baseline

G. Mention et al., The Reactor Antineutrino Anomaly, Phys. Rev. D83 (2011) 073006



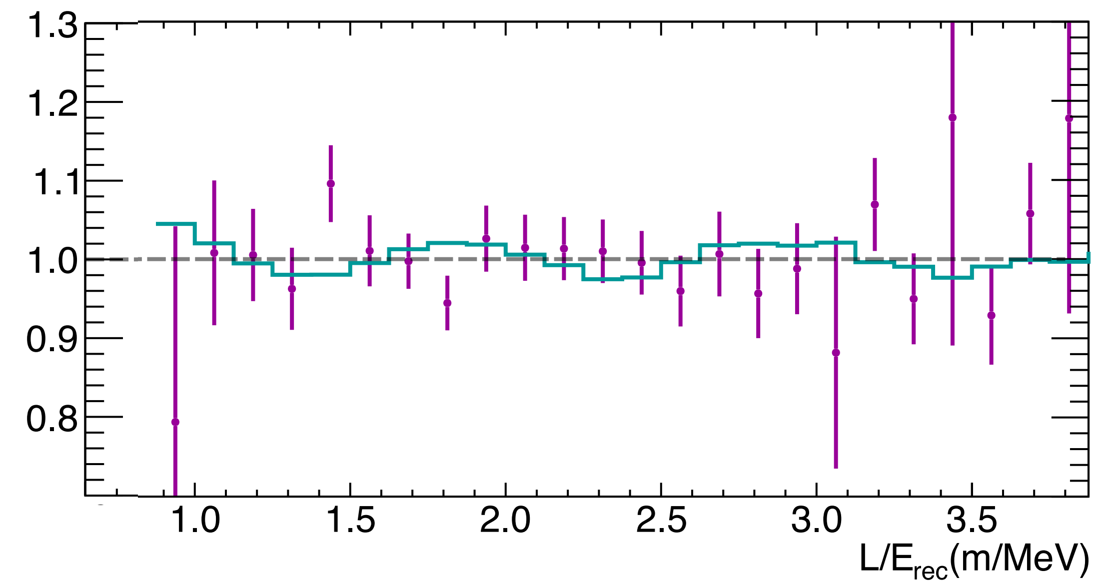
Oscillation Search



95% exclusion curve based on 33 days Reactor On operation

PROSPECT Results compared to Best Fit Solution from Mention, et al. (RAA) analysis.

Observed/Expected



Variations relative to the full integrated spectrum as a function of L/E

Conclusion & Outlook

- Data taking started in March 2018, covering one partial and one full cycle of “Reactor On”, plus “Reactor Off”
- Total of 30 days of “Reactor On” time ➥ 22K events
- We have obtained our first results from a Sterile Neutrino oscillation search. The RAA solution is disfavored.
  Preprint submitted: http://arxiv.org/abs/1806.02784
- Based on performance so far, we expect significantly higher statistical sample of events by end of 2018
- Work continuing on energy calibration, looking forward to precision spectrum results on ^{235}U neutrinos

The PROSPECT Collaboration

Ten Universities, Four National Laboratories, ≈70 Collaborators

BROOKHAVEN NATIONAL LABORATORY · Drexel University · Georgia Tech · HFIR · Lawrence Livermore National Laboratory

NIST · Oak Ridge National Laboratory · Temple University · UT · University of Waterloo · W · Yale · Le Moyne College