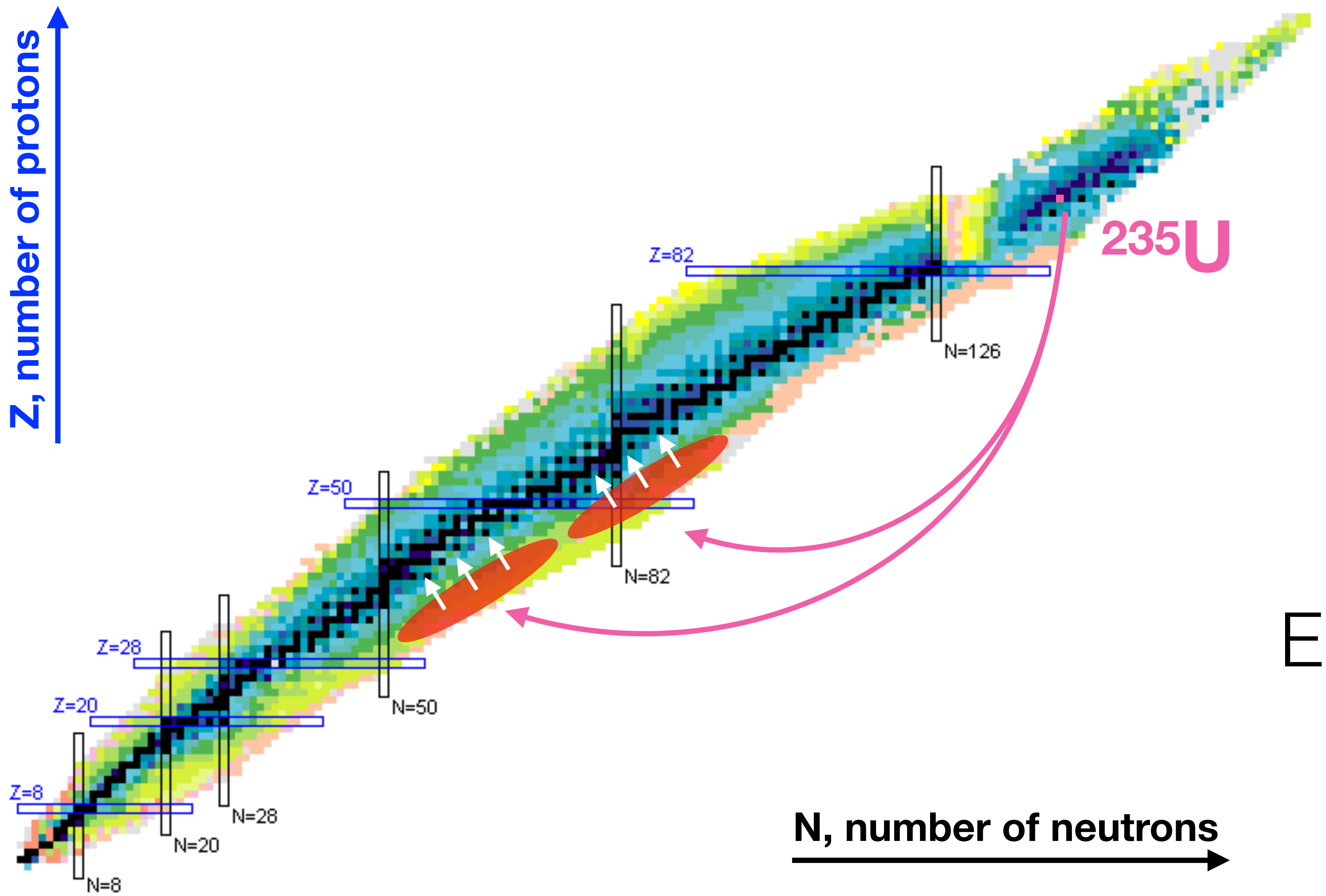
Short-Wavelength Reactor Neutrino Oscillations

^{227}Ac as a Calibration Source in the PROSPECT Experiment

Danielle (Berish) Landschoot
11/14/2019

Reactor Neutrinos



Fission

(^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U)

⇩

Beta Decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^{-} + \bar{\nu}_e$$

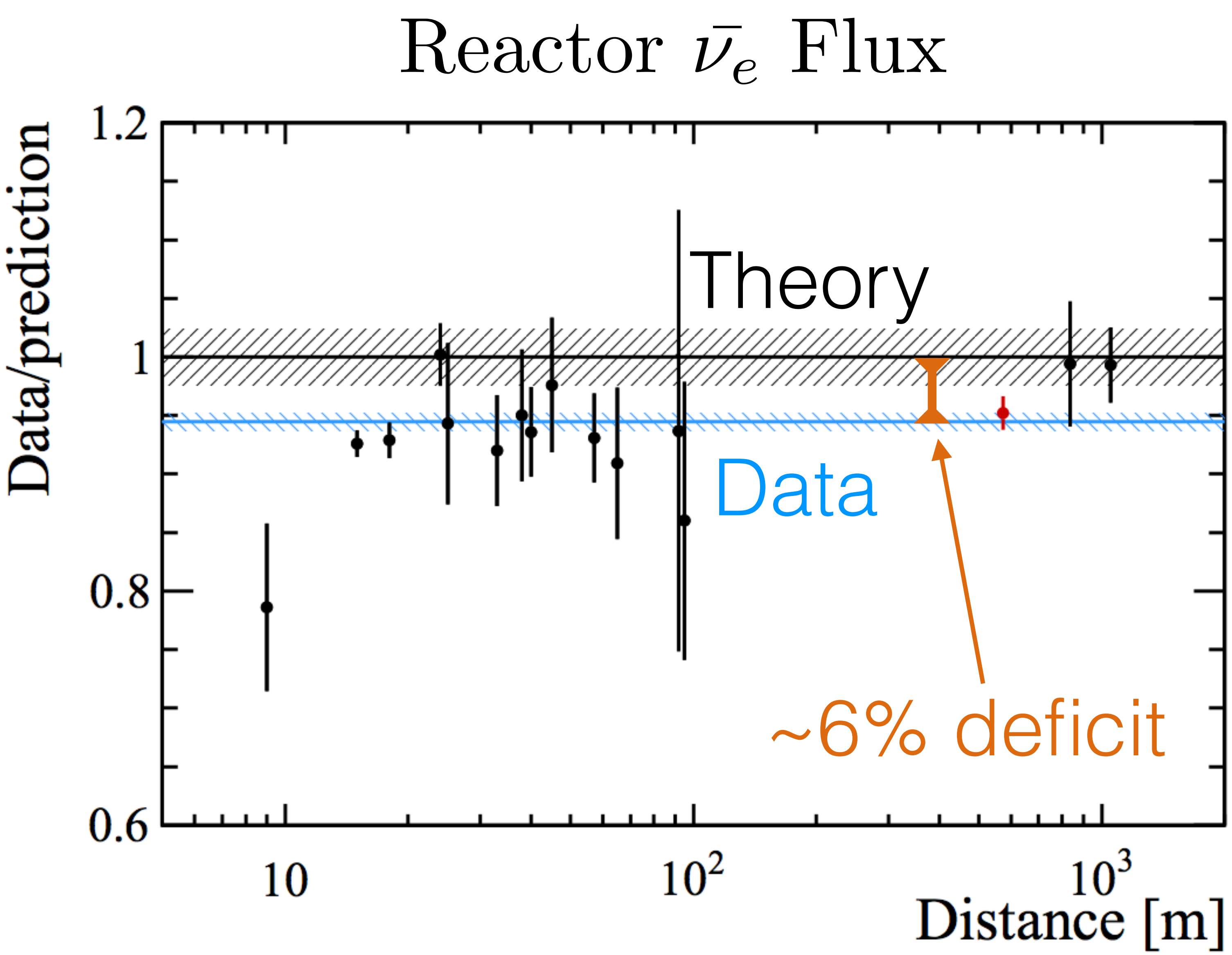
⇩

Electron antineutrinos

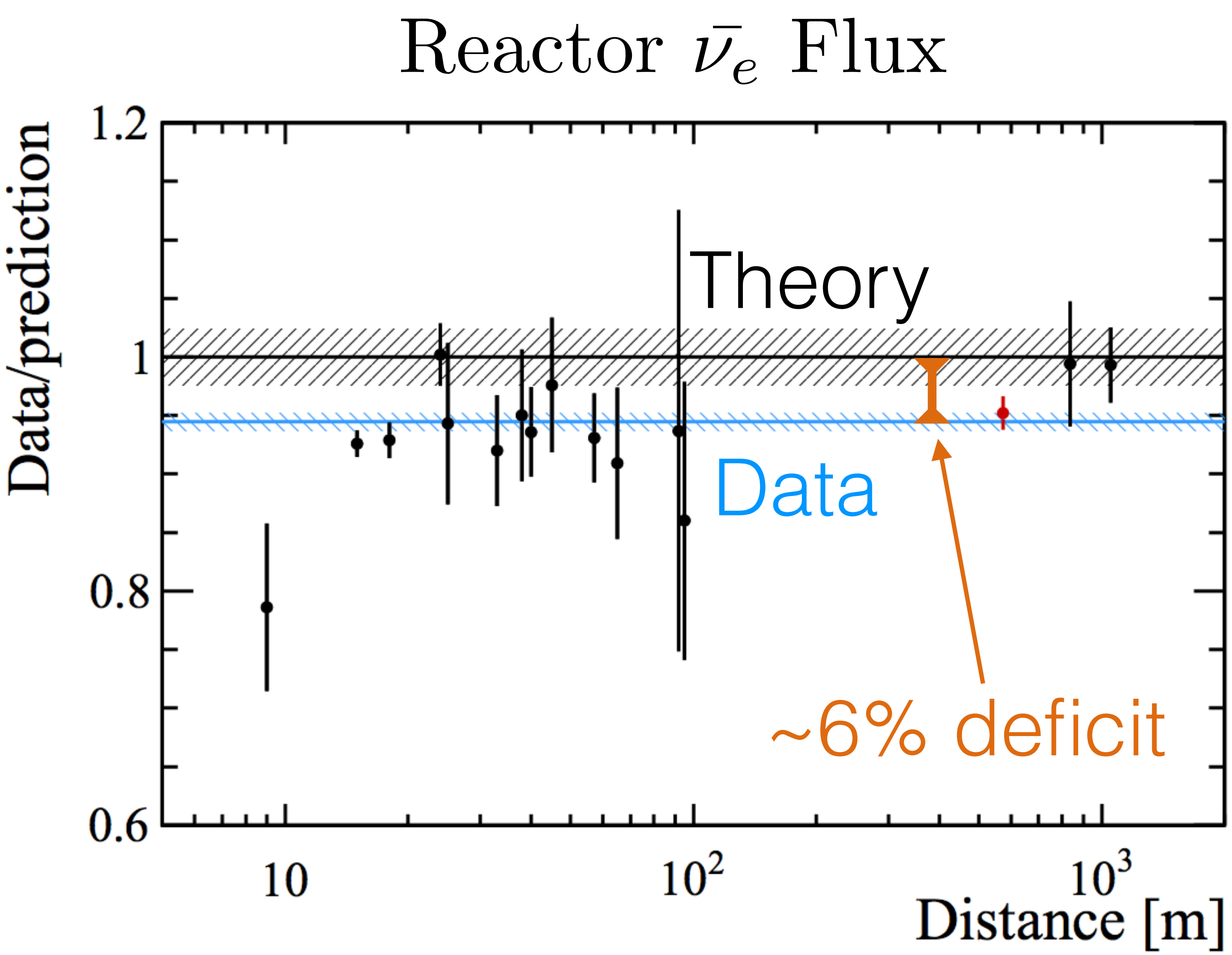
Detection via
Inverse Beta Decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

The Reactor Antineutrino Anomaly (RAA)

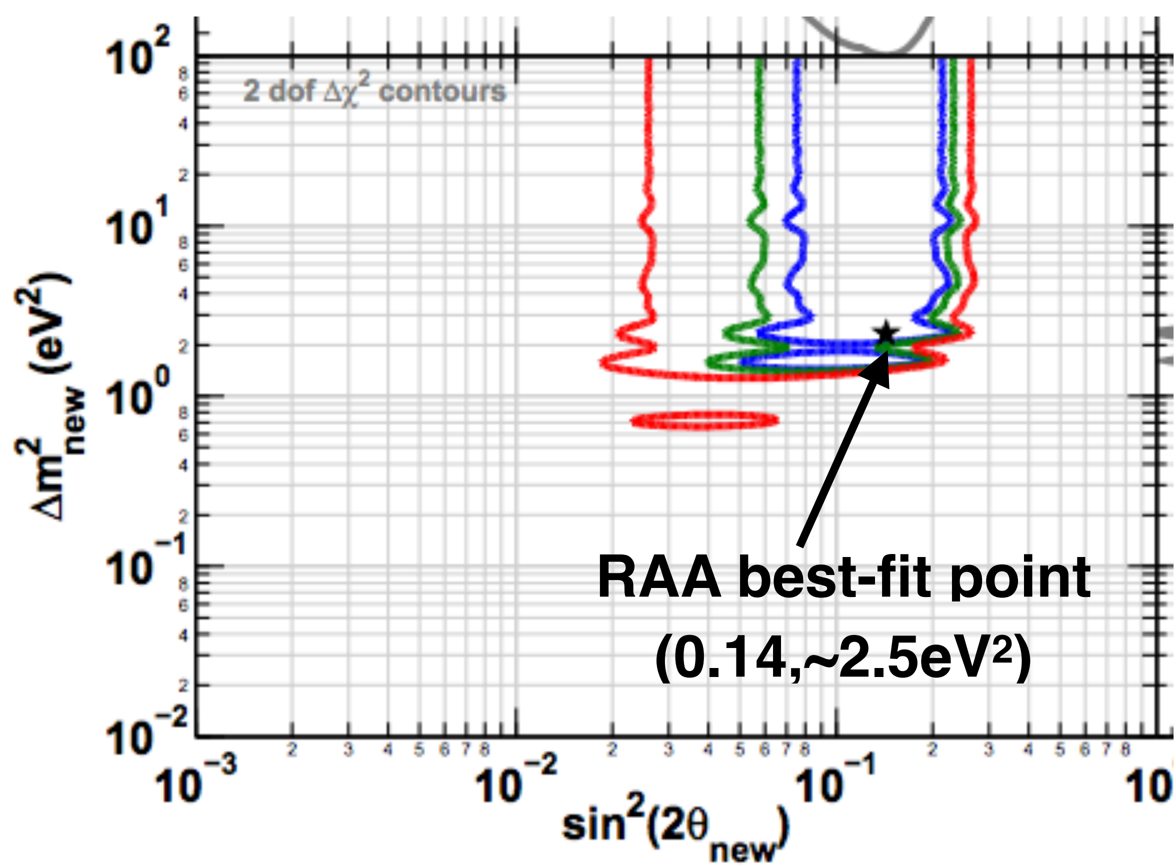


The Reactor Antineutrino Anomaly (RAA)

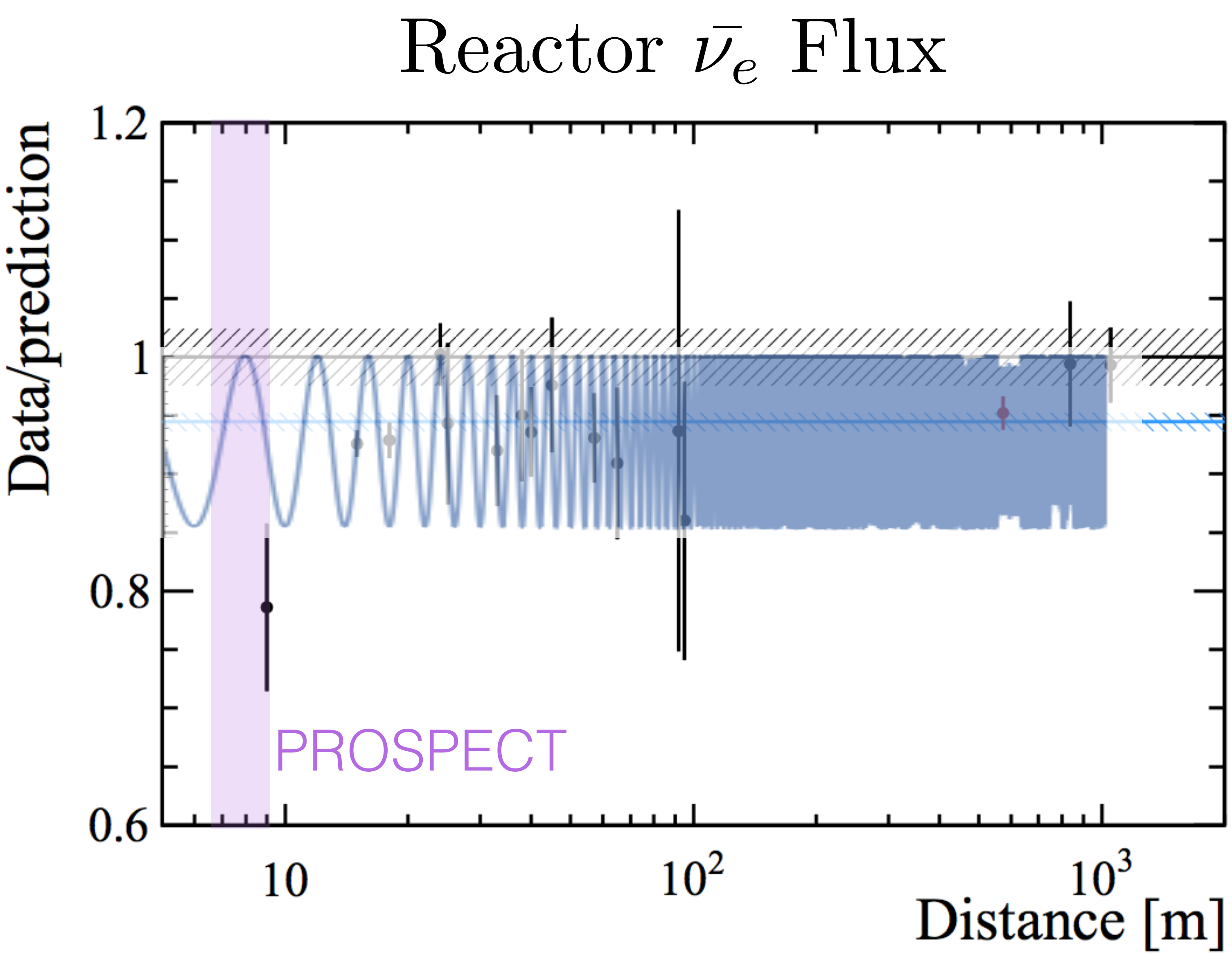


Solution: 4th generation sterile neutrino??

$$P^{2\nu}(\nu_x \to \nu_x) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

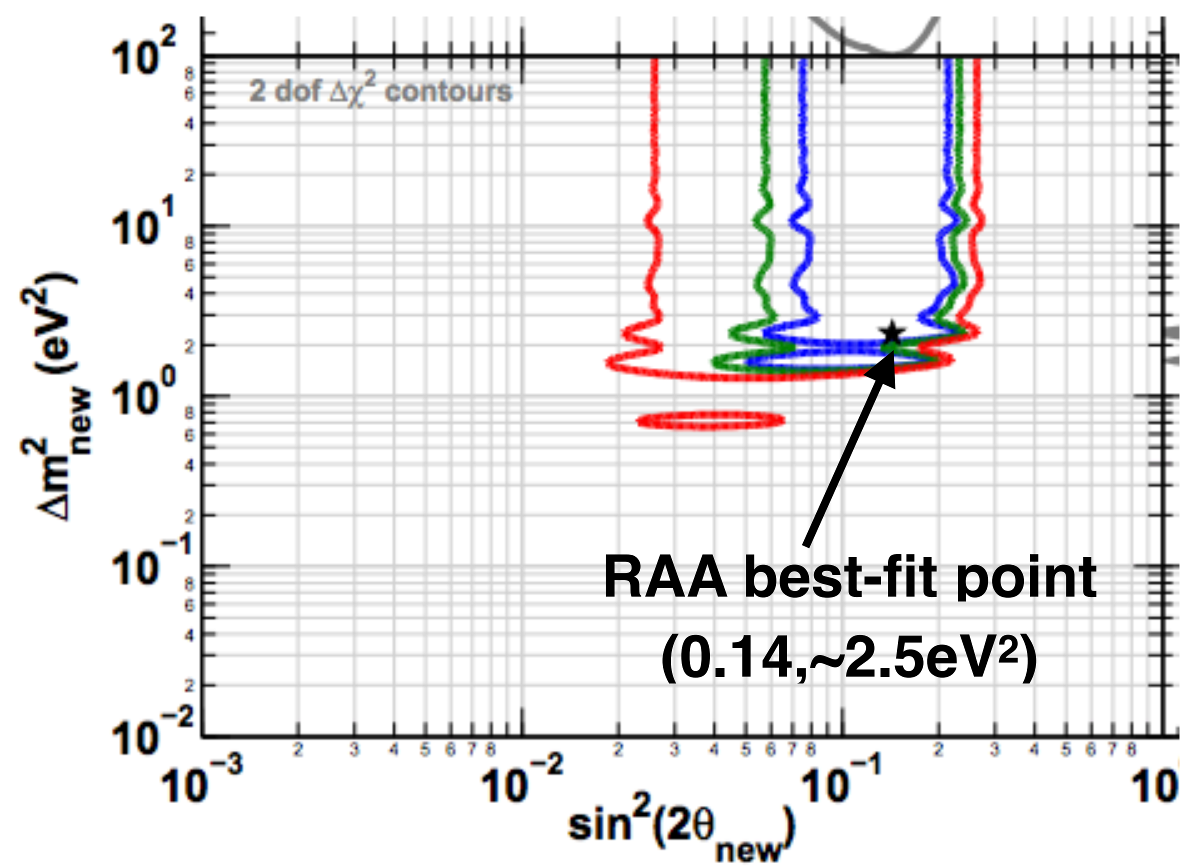


The Reactor Antineutrino Anomaly (RAA)



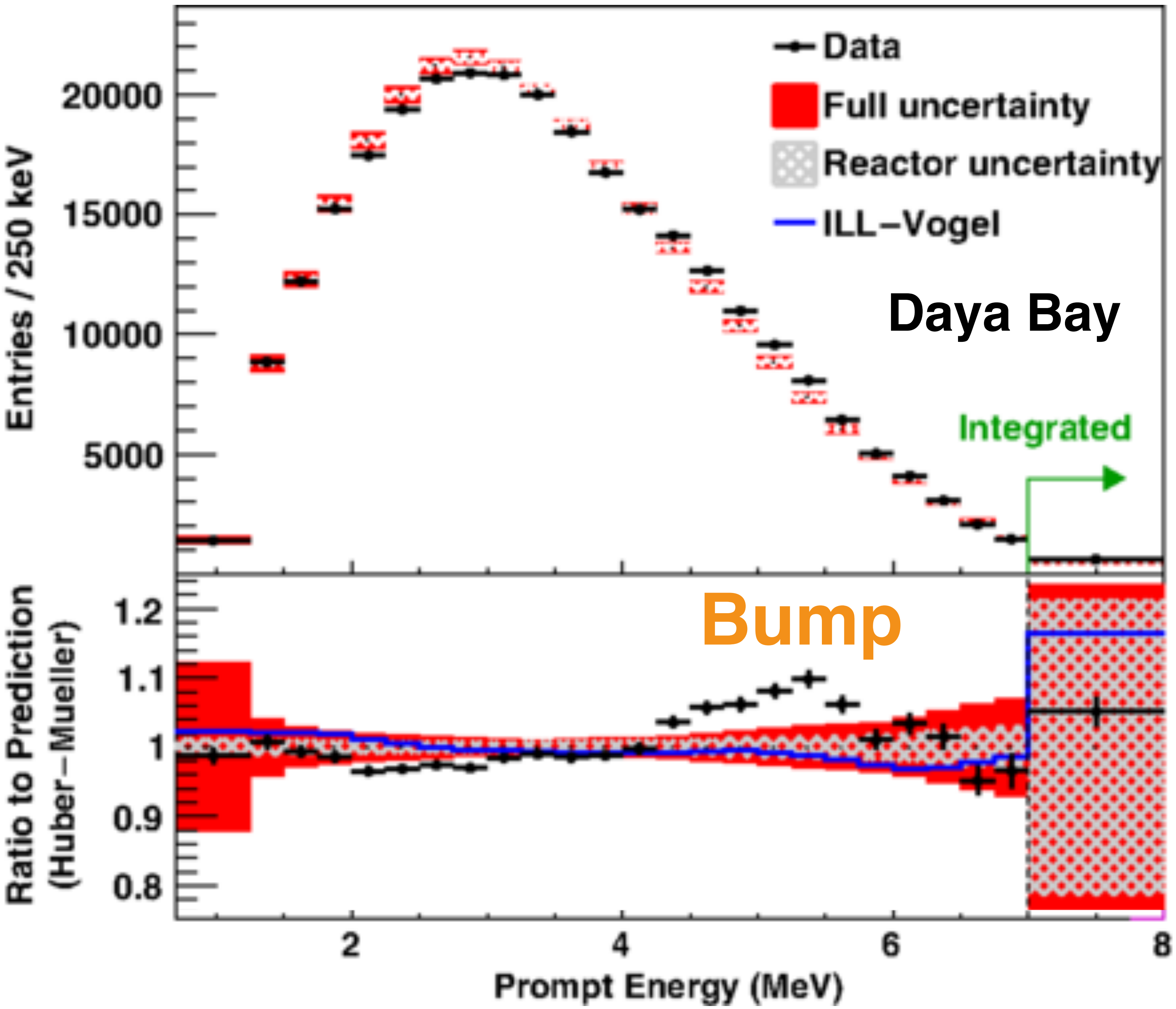
Solution: 4th generation sterile neutrino??

$$P^{2\nu}(\nu_x \rightarrow \nu_x) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$



Spectrum Anomaly

Prompt Energy



Really hard to calculate!!

Cannot be explained by a sterile neutrino. Points to incomplete reactor models.

The PROSPECT Experiment

Precision Reactor Oscillation and SPECTrum Experiment

Physics Goals:

(1) Search for meter scale sterile neutrino oscillations, *PRL 121 (2018) 251802*

(2) Measure the ^{235}U antineutrino spectrum, *PRL 122 (2019) 251801*

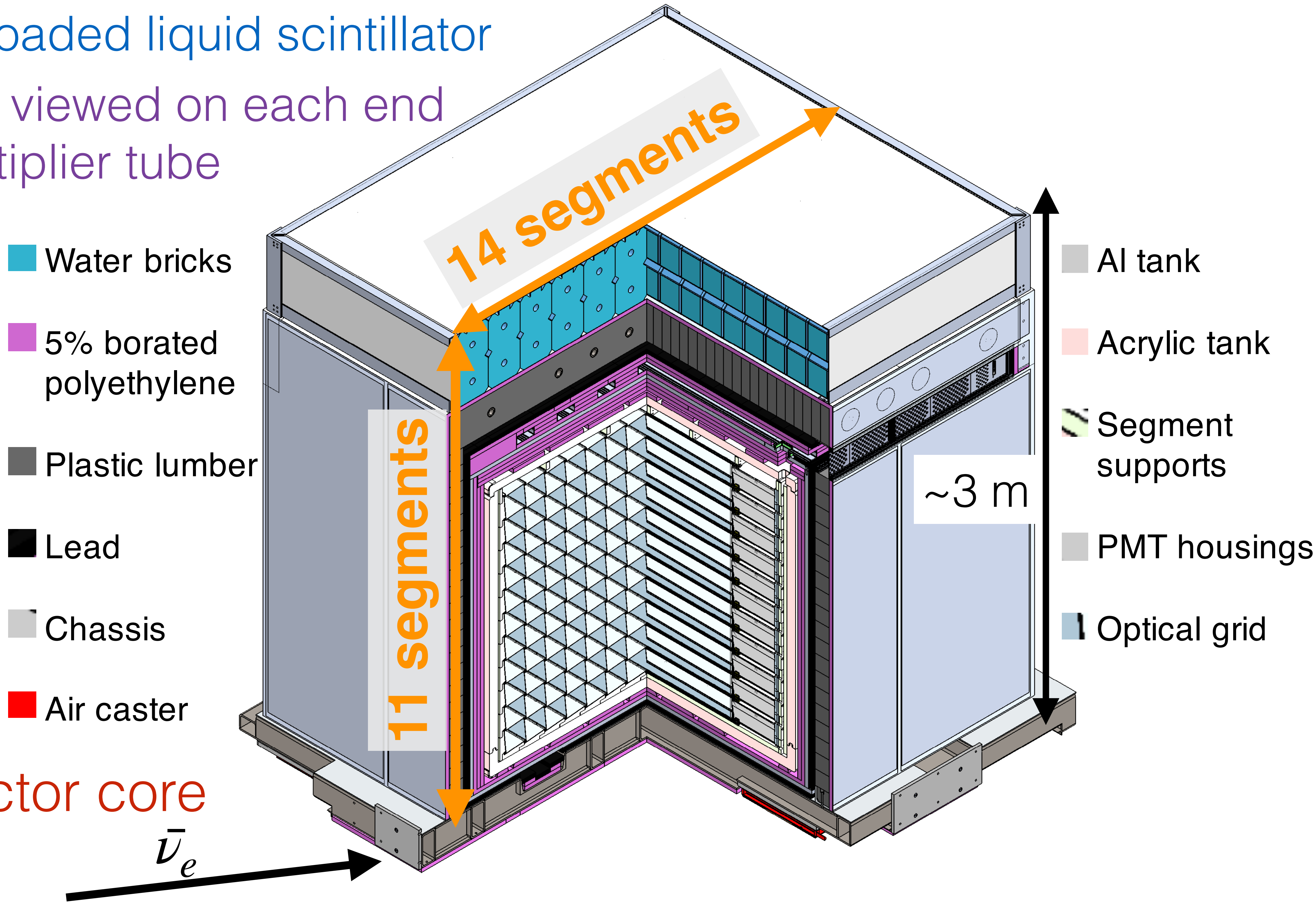
Located at the High Flux Isotope Reactor at Oak Ridge National Laboratory

PROSPECT Antineutrino Detector

154 optically separated segments

Filled with ^{6}Li loaded liquid scintillator

Each segment viewed on each end by a photomultiplier tube

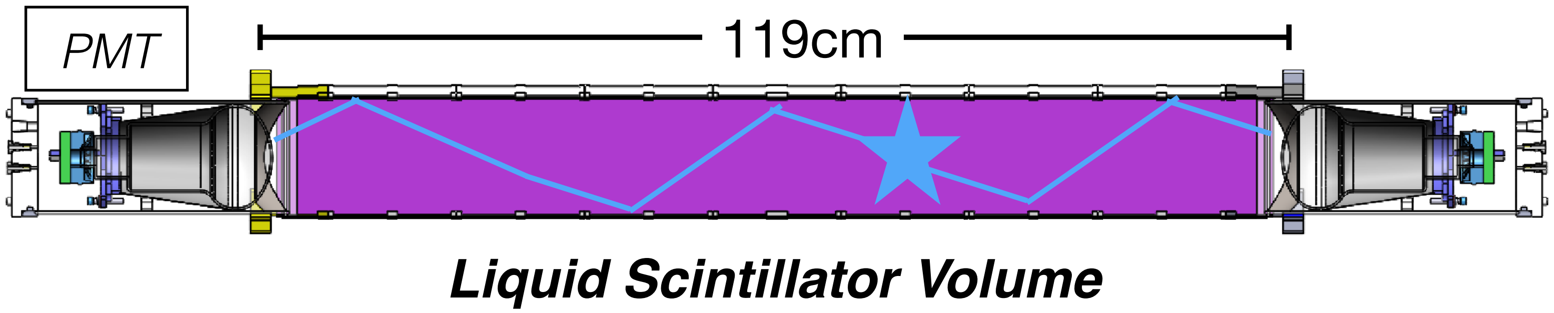


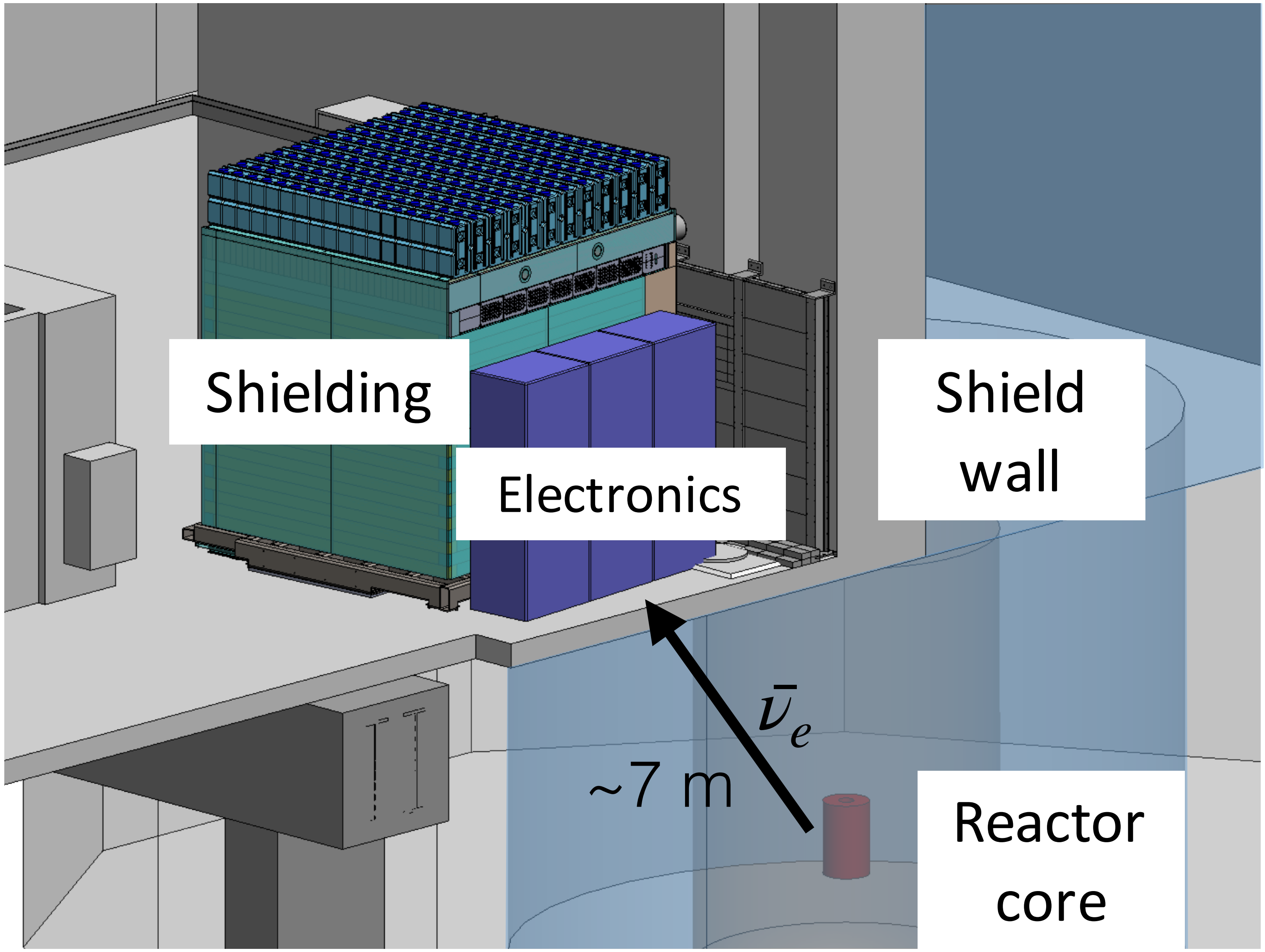
~7 m to reactor core

$\bar{\nu}_e$

PROSPECT Antineutrino Detector

Segment Design

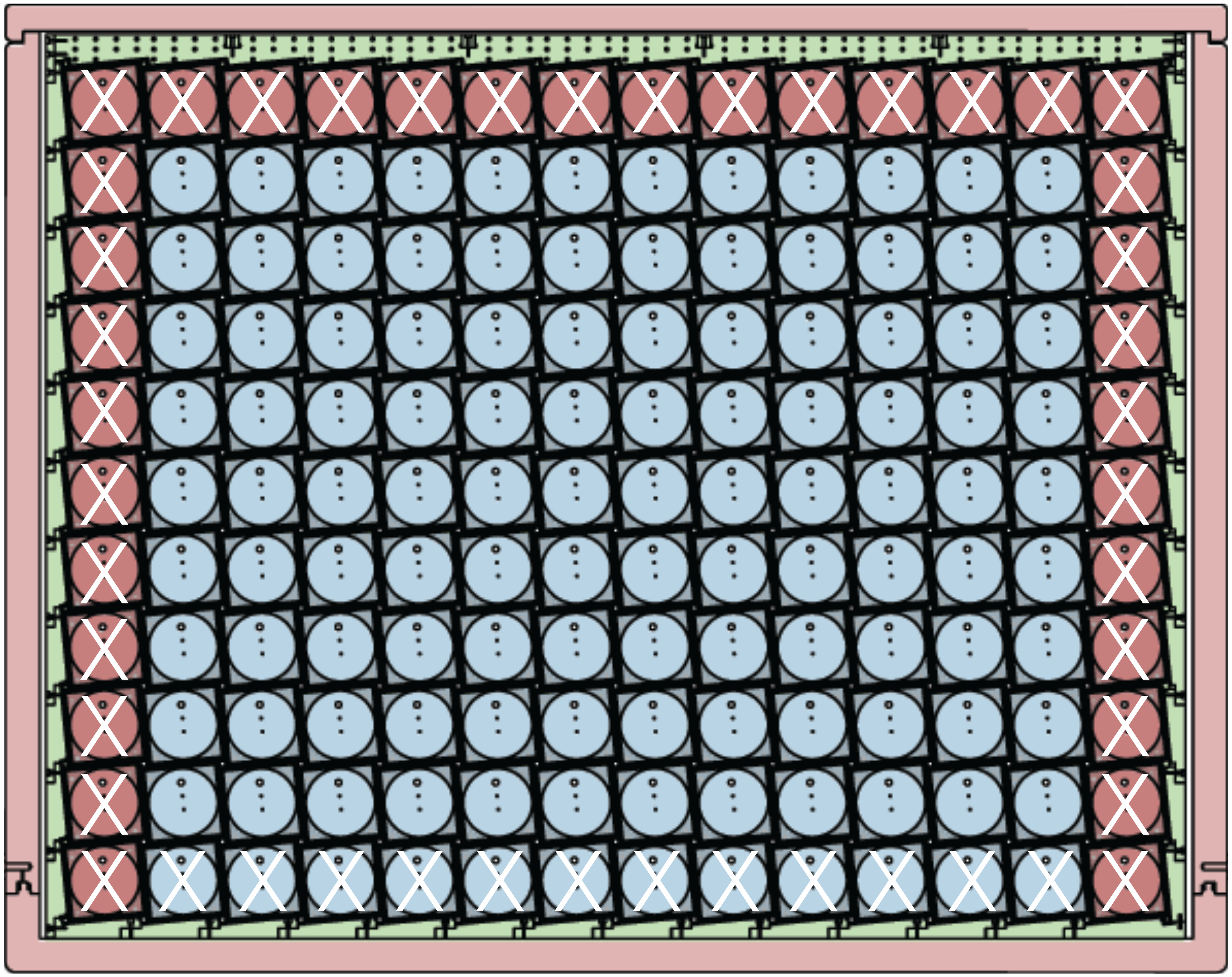




Photomultiplier Tube (PMT) Configuration

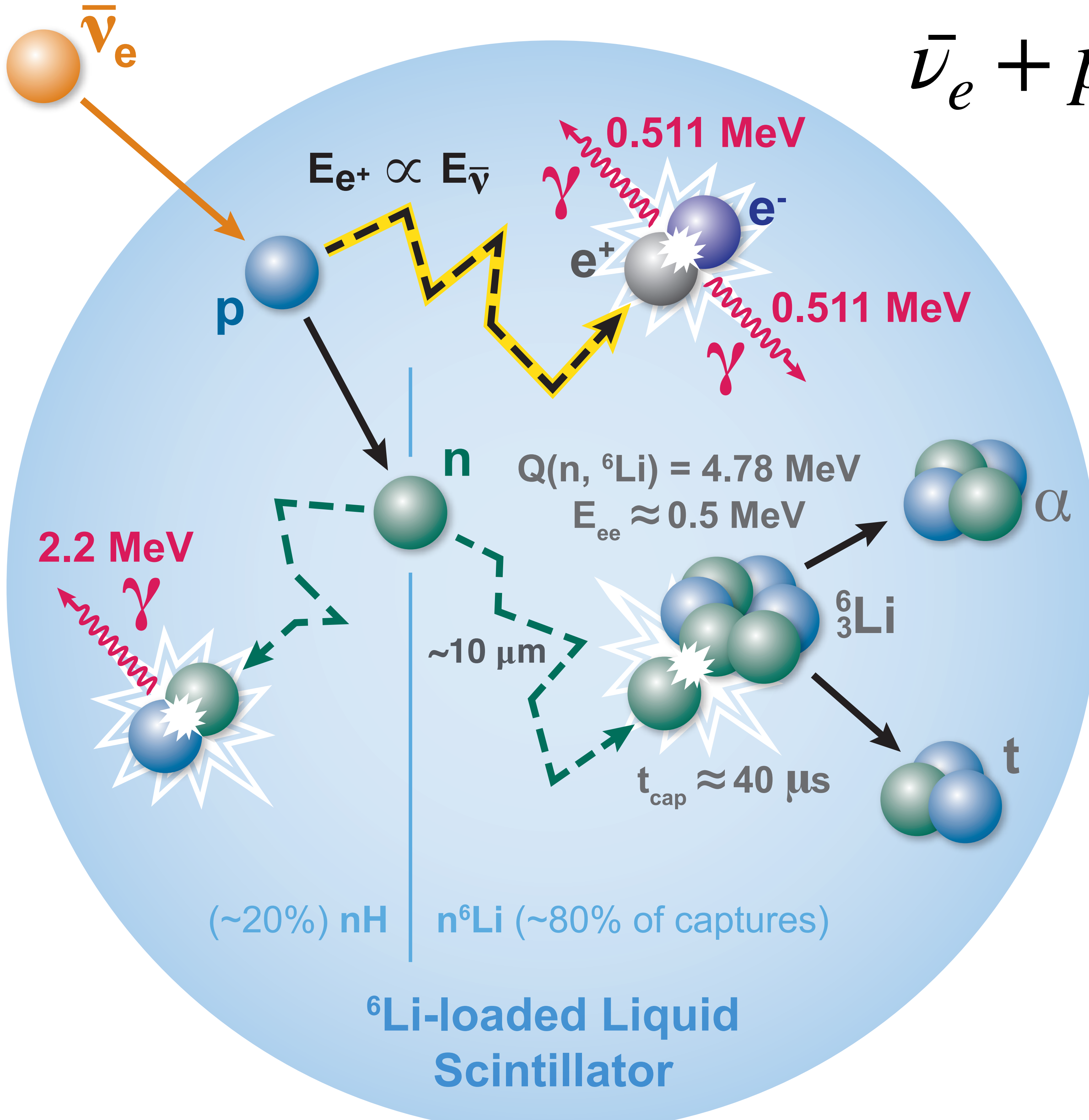
68 Electron Tubes (ET) - Outer Shell

240 Hamamatsu Tubes - Fiducial Volume



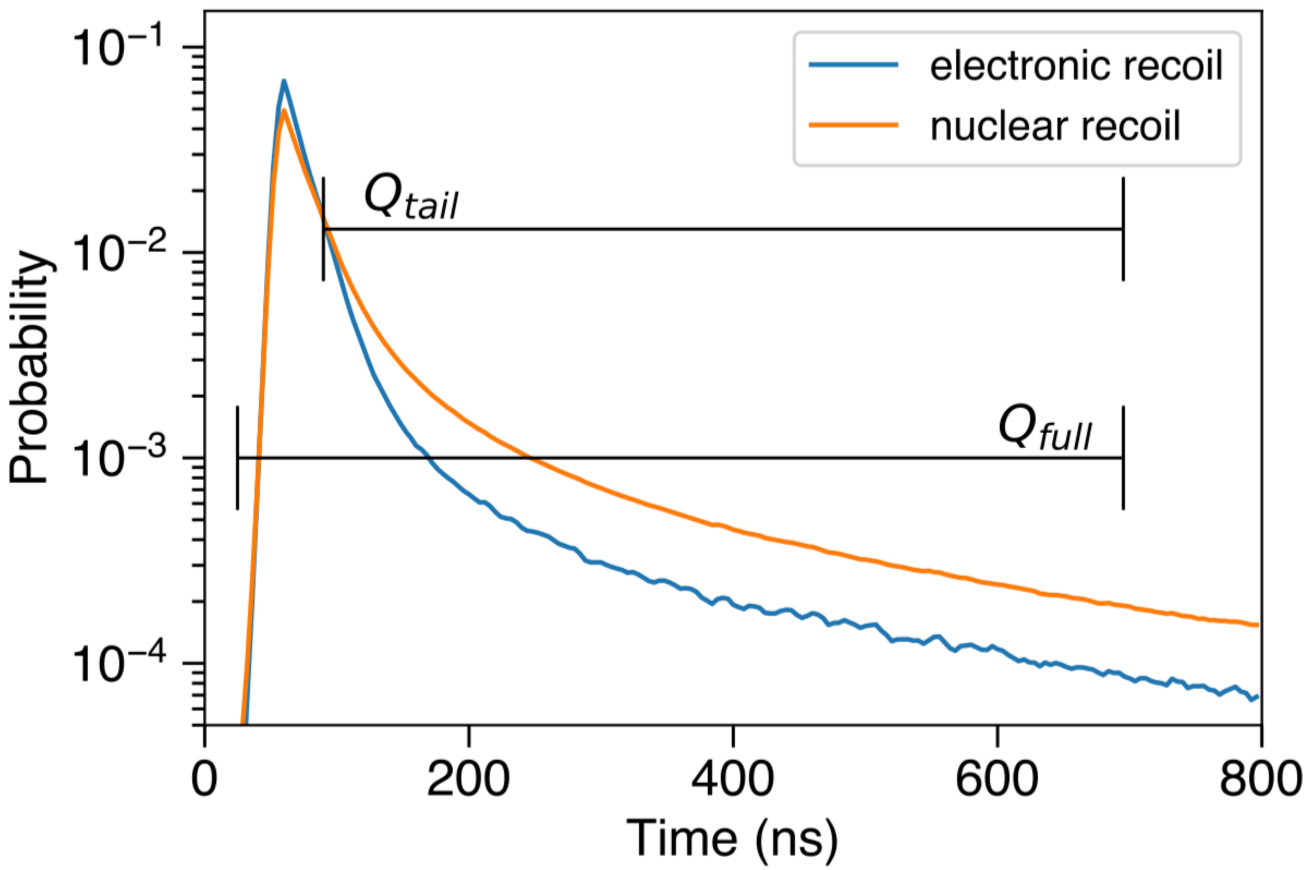
PROSPECT IBD Detection

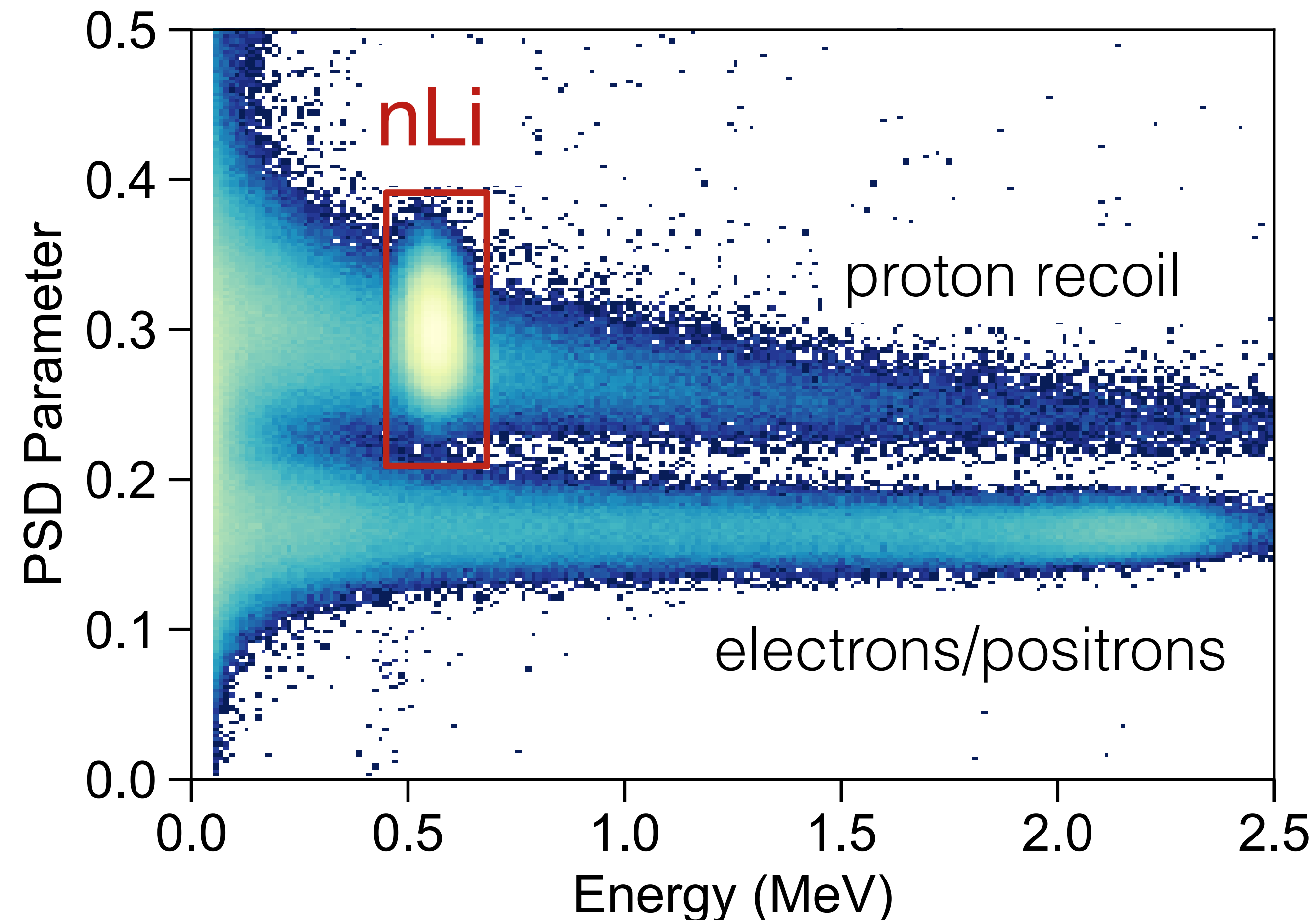
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Pulse Shape Discrimination (PSD)

Allows us to distinguish between particle types

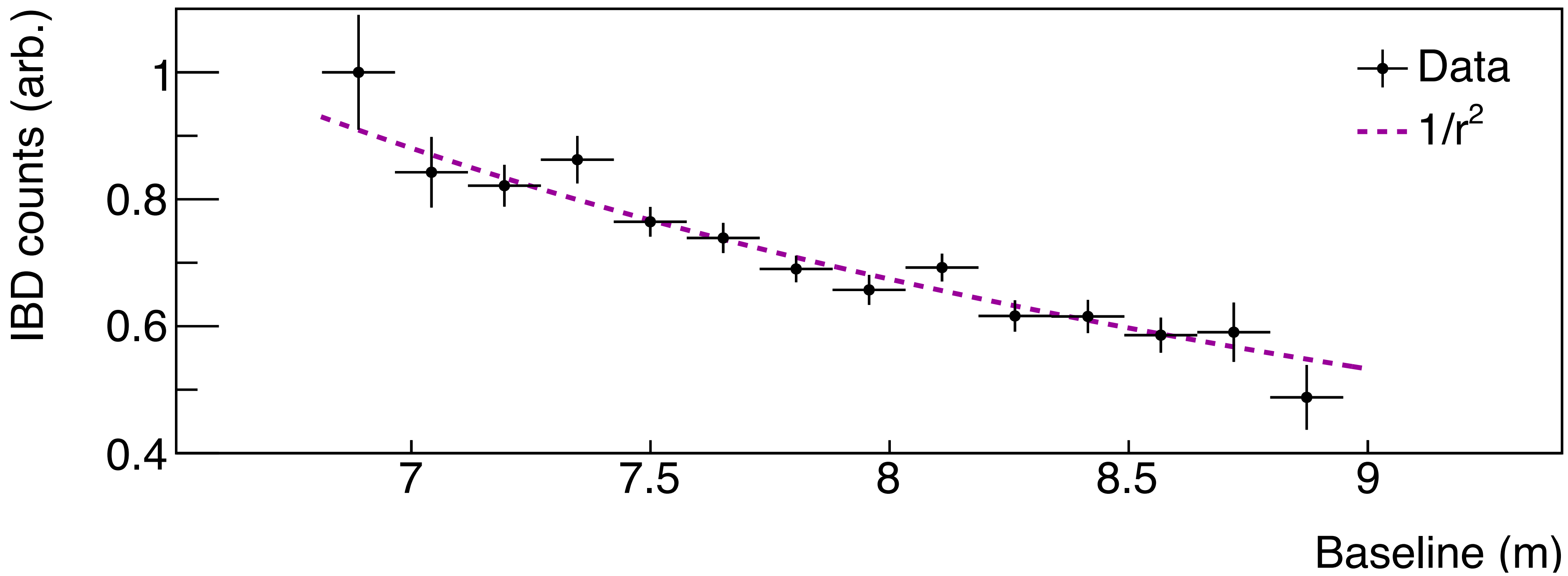




$$PSD = \frac{Q_{tail}}{Q_{total}}$$

Oscillation Search

IBD rates should fall like $1/r^2$ as a function of distance from the reactor
Any deviation from this could point to the existence of a sterile neutrino!



With enough statistics, volume variations in the detector could cause a deviation from $1/r^2$ behavior, with *no* sterile neutrino present

It is important that we understand our relative segment-to-segment volume variations!

^{227}Ac as a Calibration Source

$$^{227}\mathrm{Ac} \rightarrow \ldots \rightarrow ^{219}\mathrm{Rn} \rightarrow ^{215}\mathrm{Po} + \alpha \rightarrow ^{211}\mathrm{Pb} + \alpha$$

$t_{1/2} = 21.772$ yrs $\quad t_{1/2} = 3.96$ s $\quad t_{1/2} = 1.781$ ms

	E_α [keV]	I_α %		E_γ [keV]	I_γ %
^{219}Rn	6425.0(10)	7.5(6)		271.23(1)	10.8(6)
	6530(2)	0.110(10)		401.81(1)	6.6(4)
	6552.6(10)	12.9(6)		130.60(3)	0.13(9)
	6819.1(3)	79.4(10)			
^{215}Po	7386.1(8)	99.999770(20)			

Double α coincidence = only a tiny amount of ^{227}Ac needed
(~3 mHz per segment, 1 decay every 5 minutes)

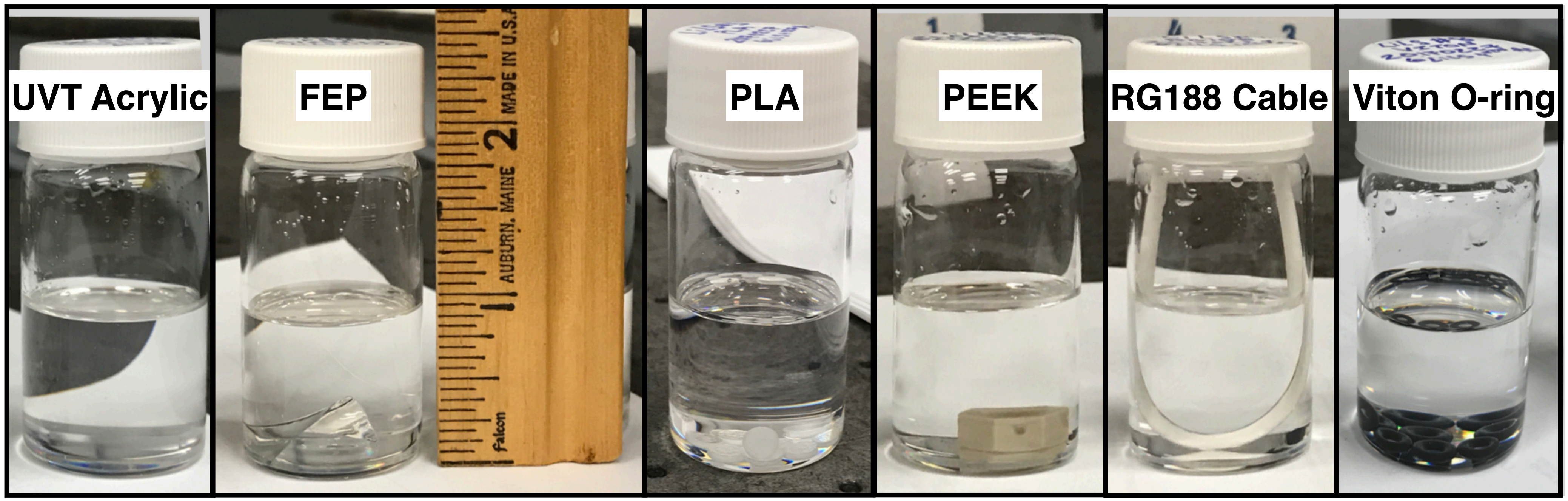
Mono-energetic ^{215}Po alpha decay

Highly localized signal

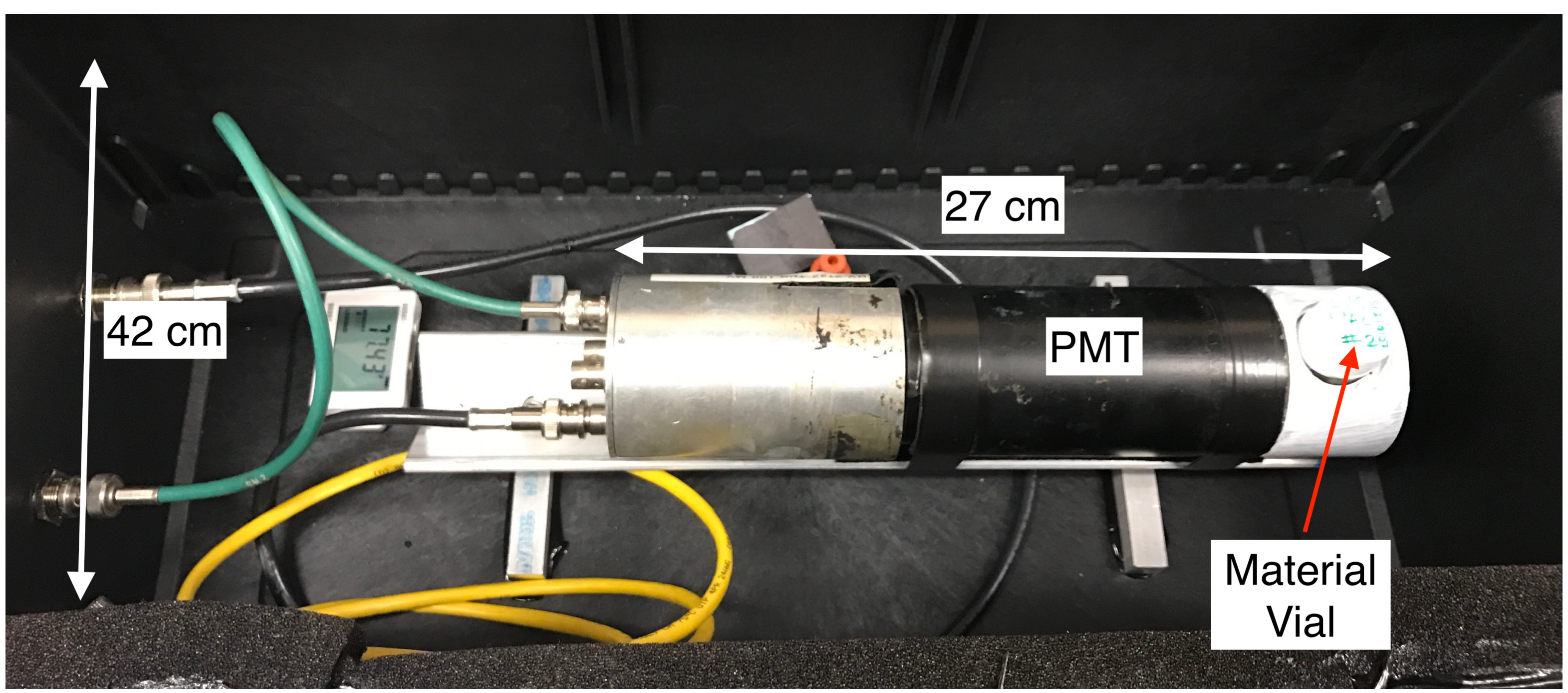
Used to measure relative segment-to-segment volume variations

Material Compatibility

To determine that ^{227}Ac did not adsorb onto detector materials or degrade the scintillator

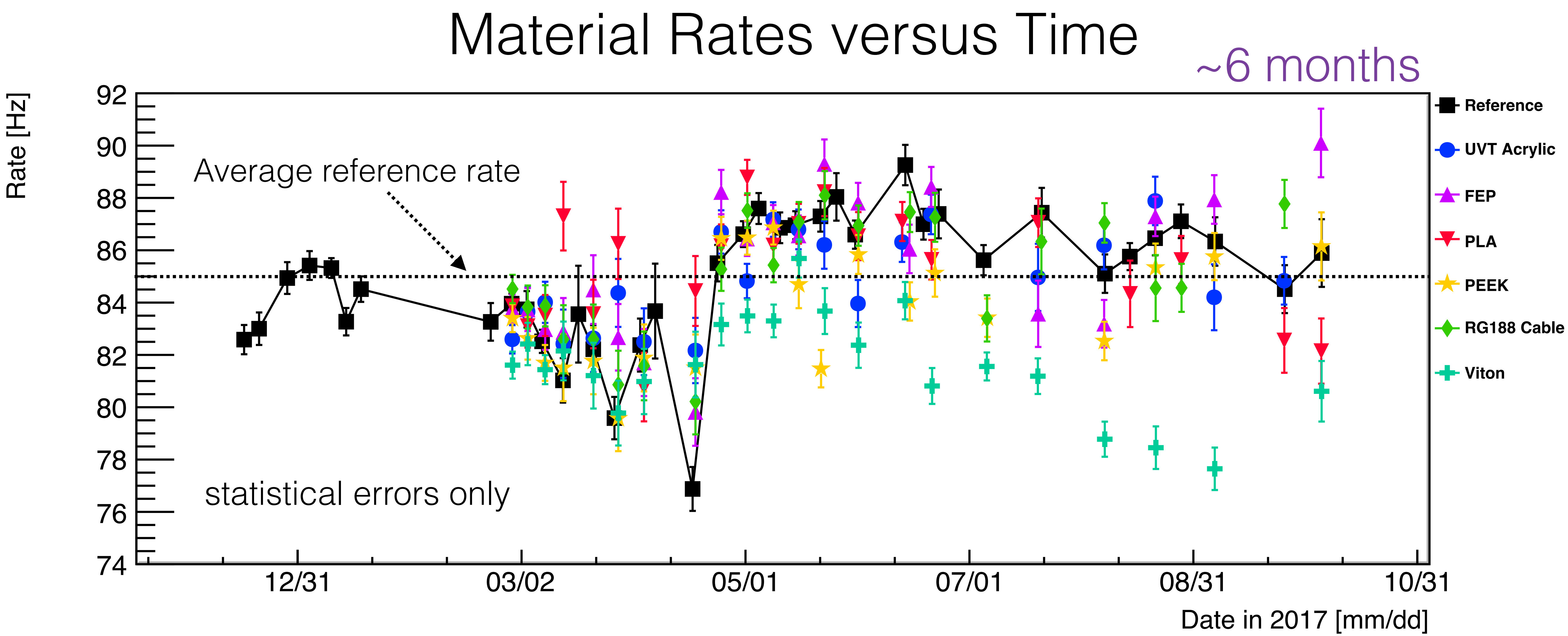


+ Reference vial (no material)



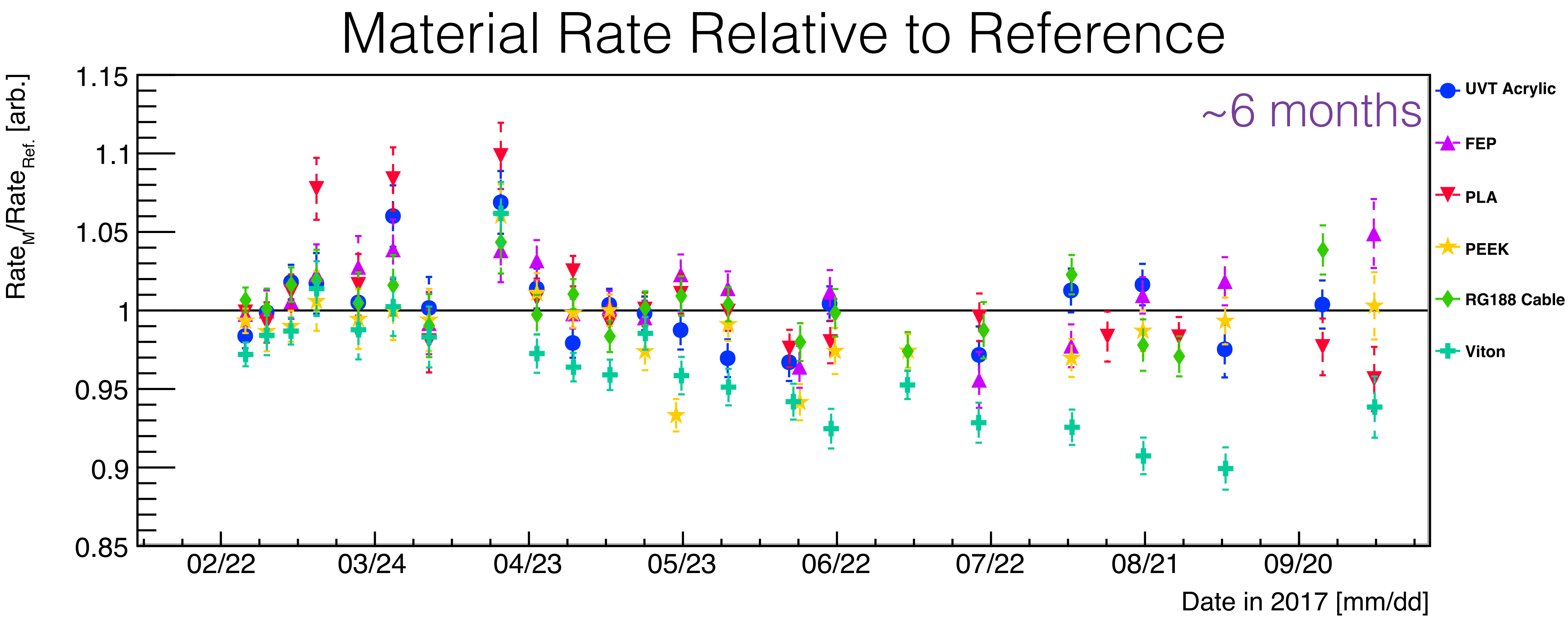
Surface to volume ratio, and ^{227}Ac rate, *much* higher than in detector!

Material Study Results



As much as 10% variation → large systematic errors

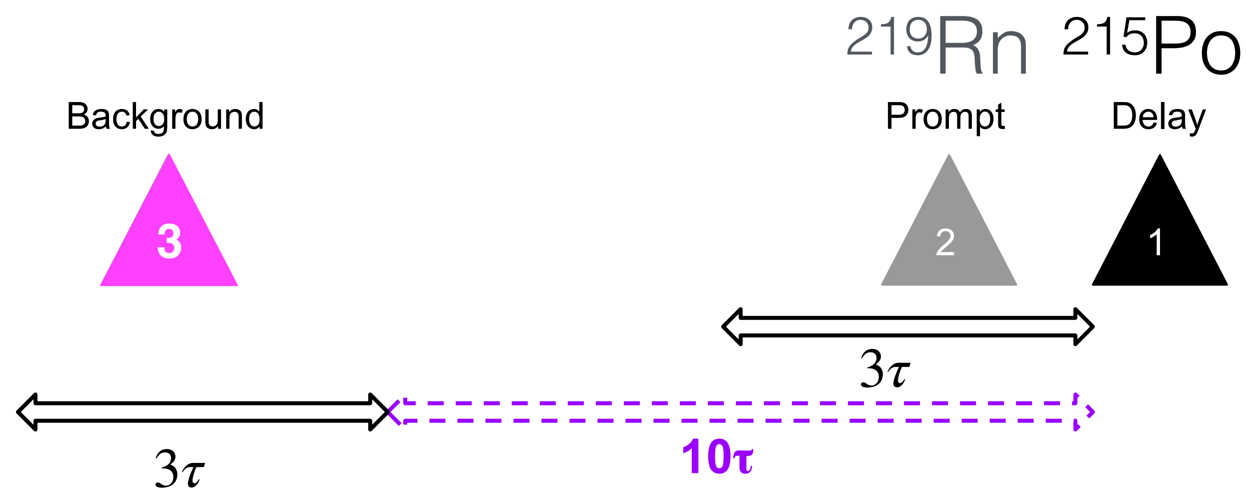
Material Study Results



No clear sign of adsorption* or degradation of LS

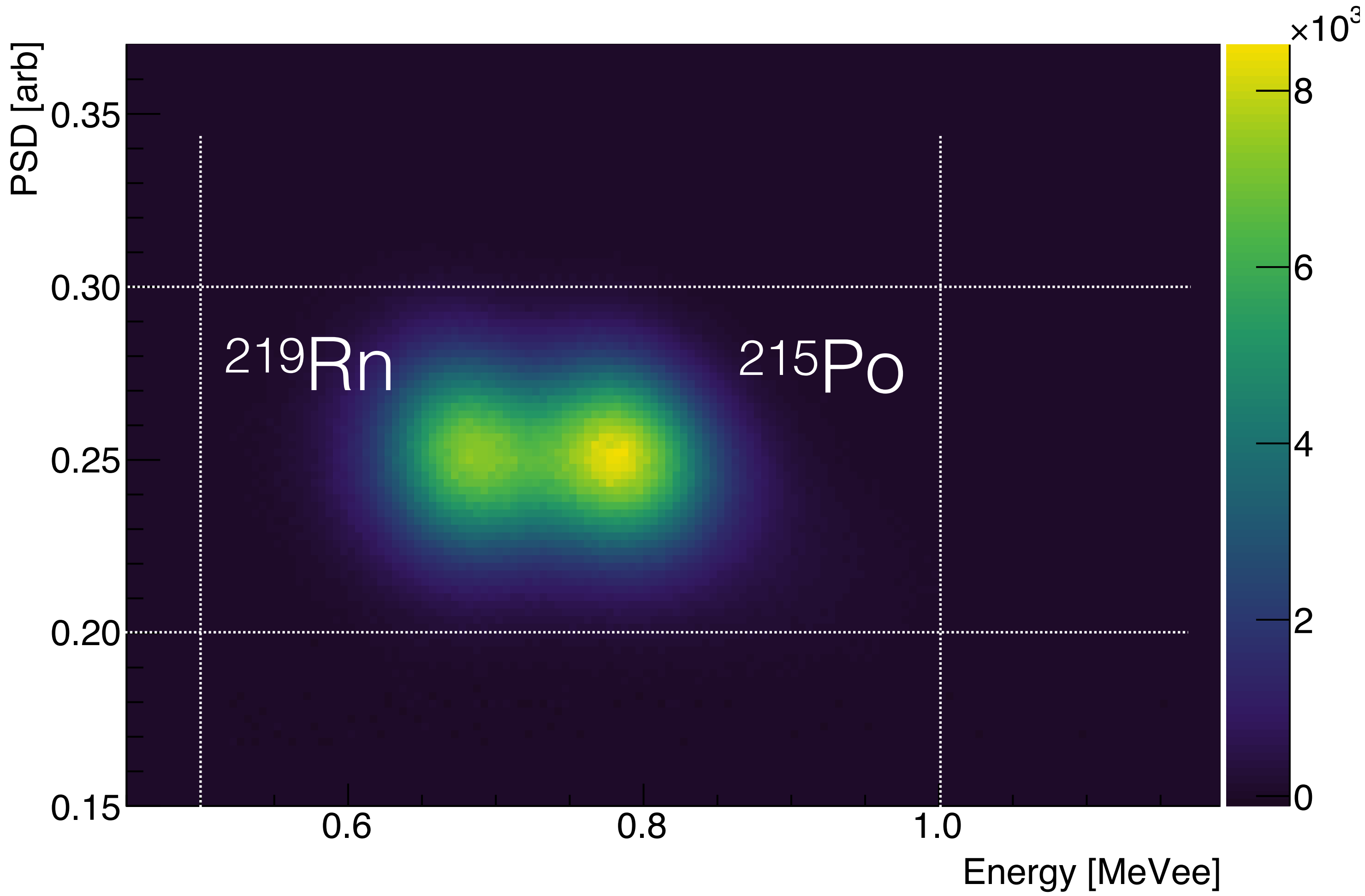
*decrease in viton due to threshold effects, not adsorption

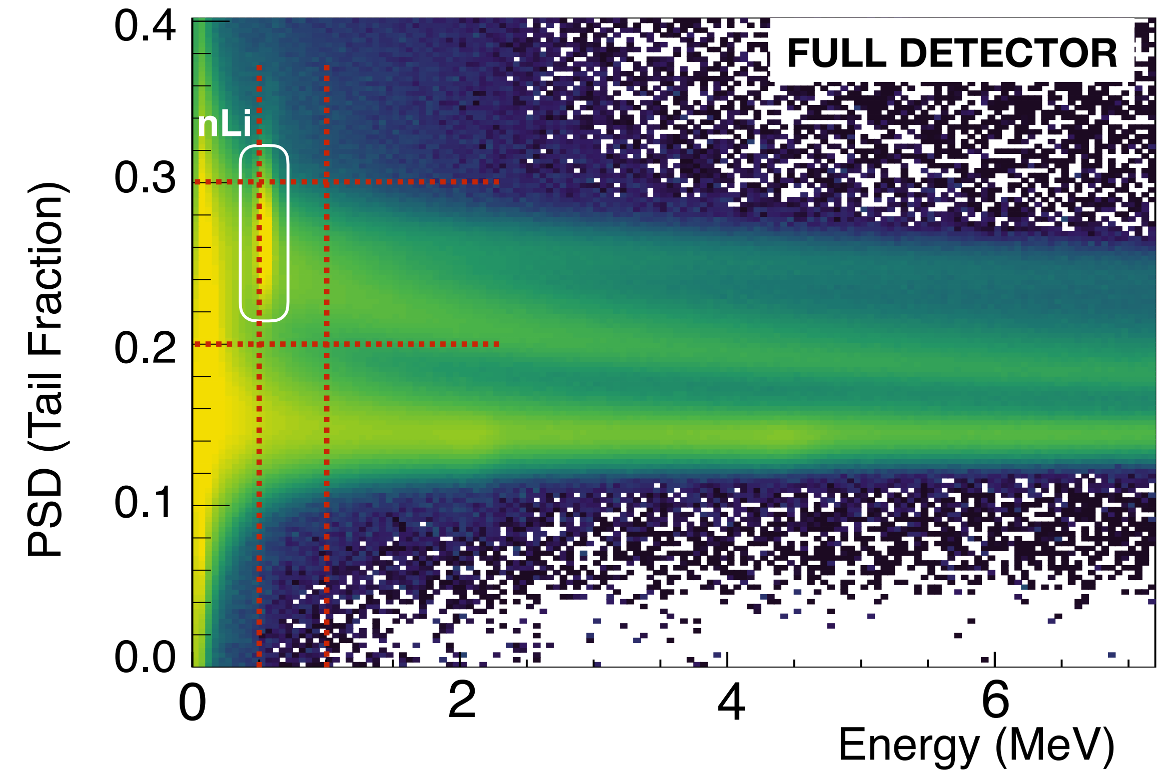
^{227}Ac in the PROSPECT Detector



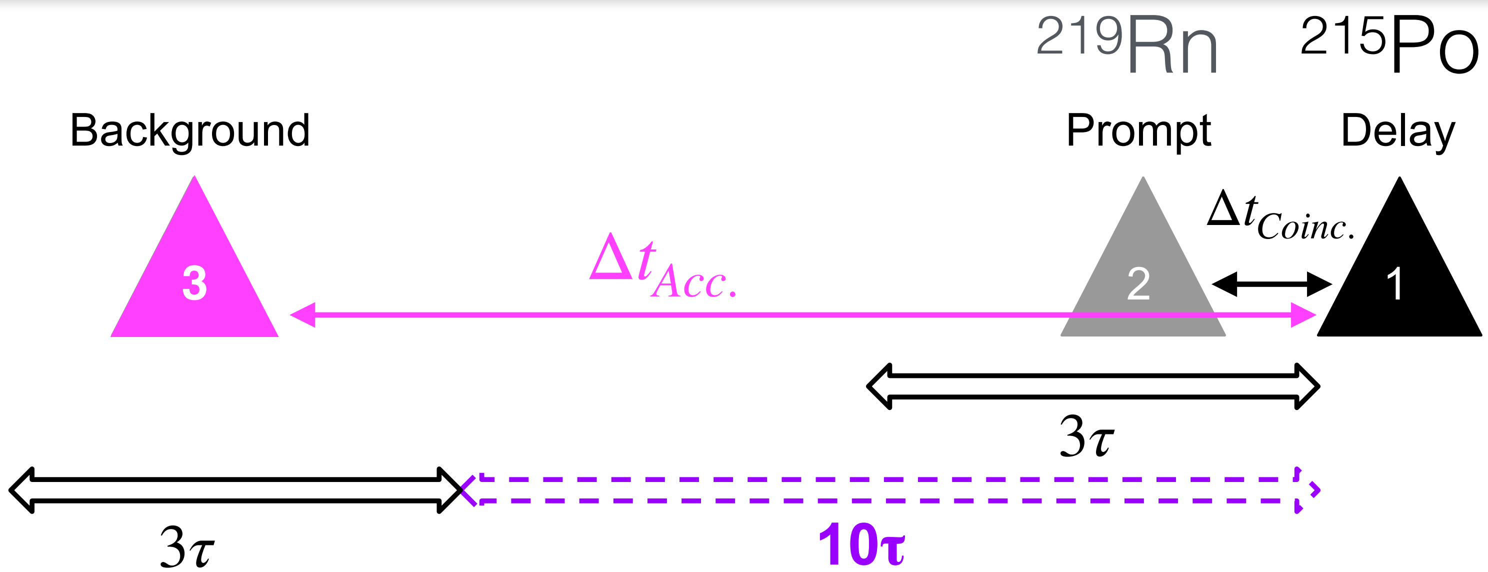
$$\tau = \tau_{Po} = 2.57 \text{ ms}$$

Segment-Po = Segment-Rn

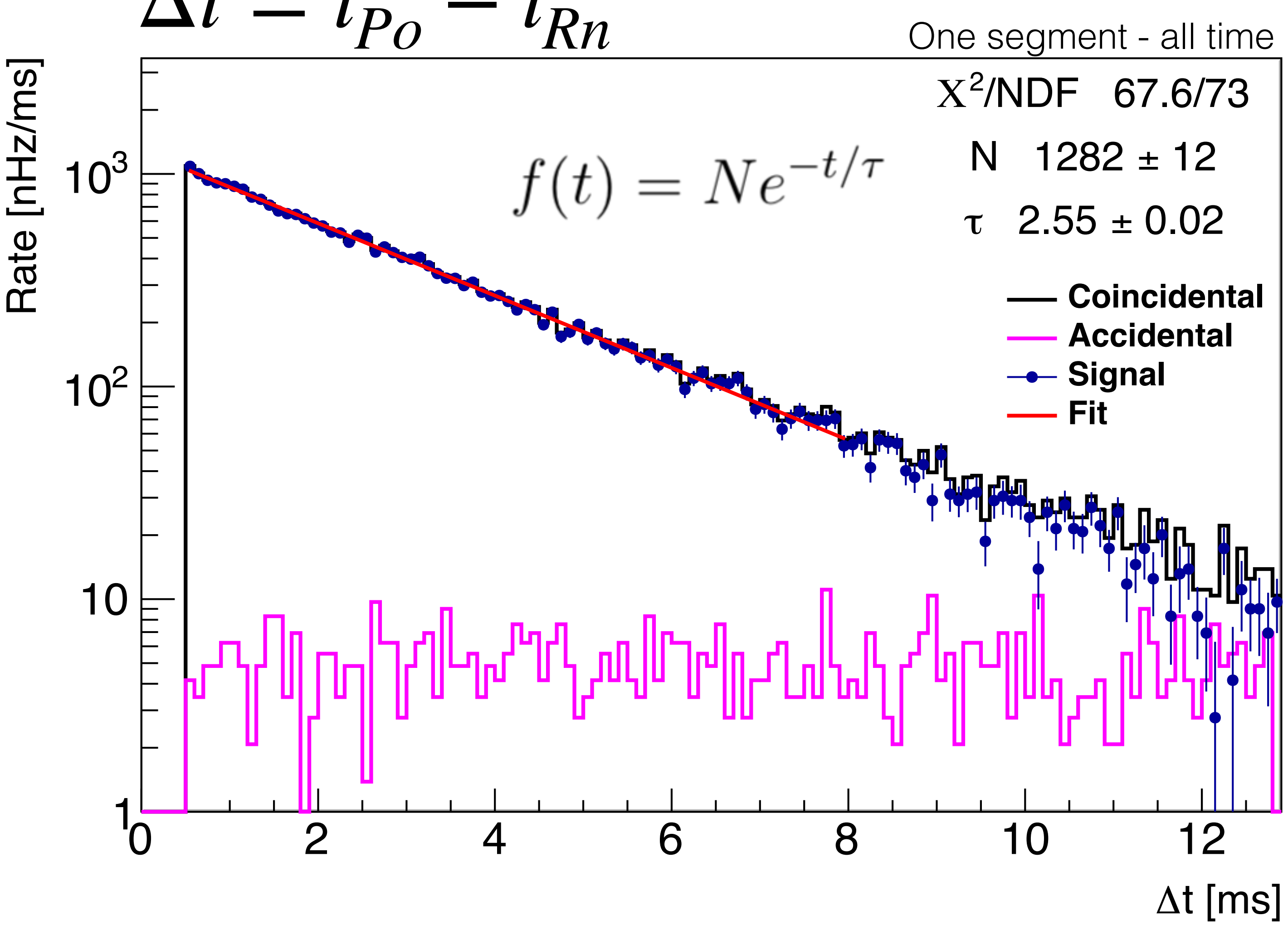




Measuring the ^{227}Ac Decay Rate



$$\Delta t = t_{Po} - t_{Rn}$$



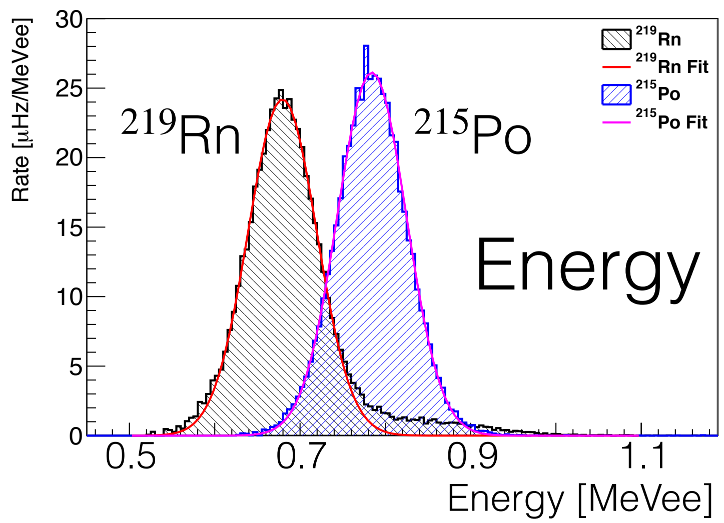
$$R = \frac{N\ \tau}{\Delta t\text{-bin-width} \times \text{livetime} \times \text{efficiency}}$$

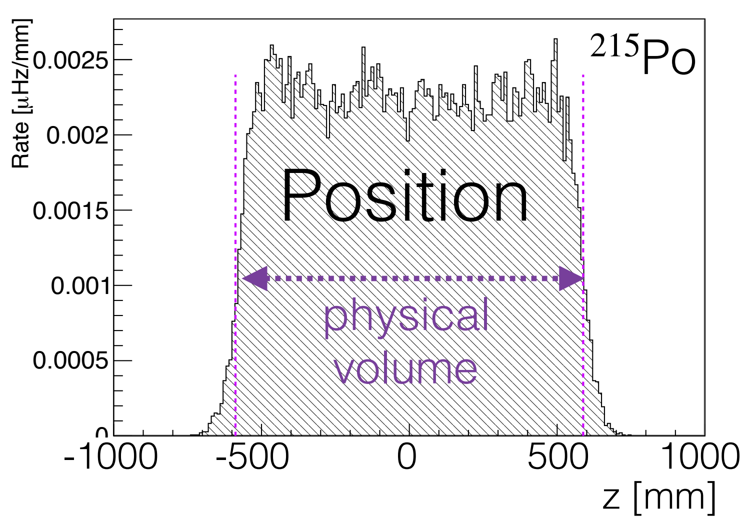
Efficiency > 99.9%

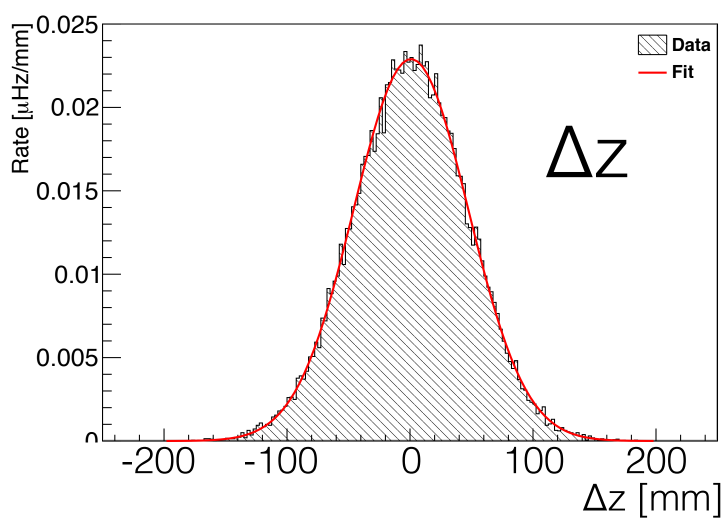
Livetime = 4011.7 hrs

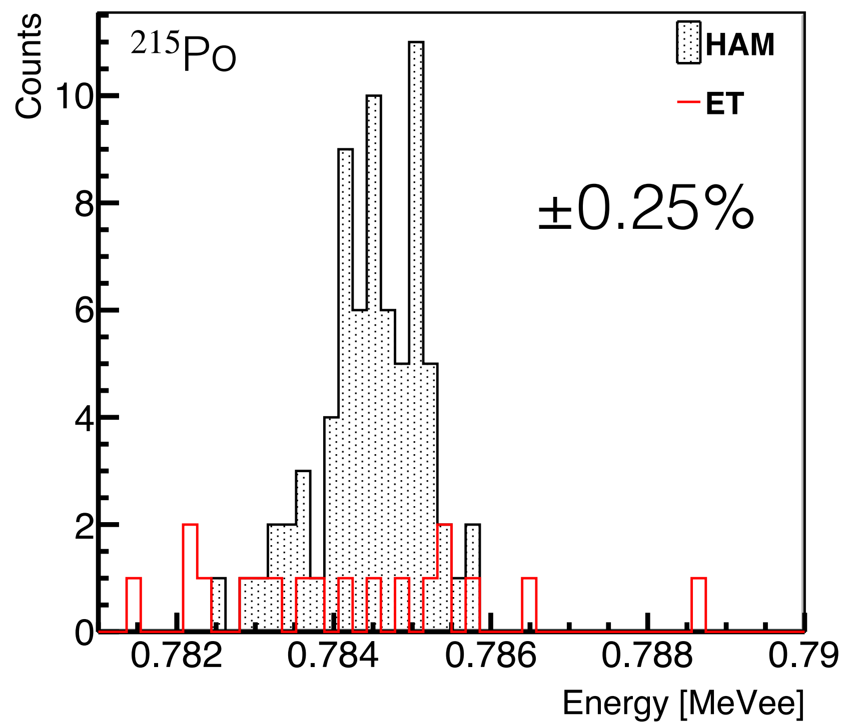
Segment-to-Segment Stability

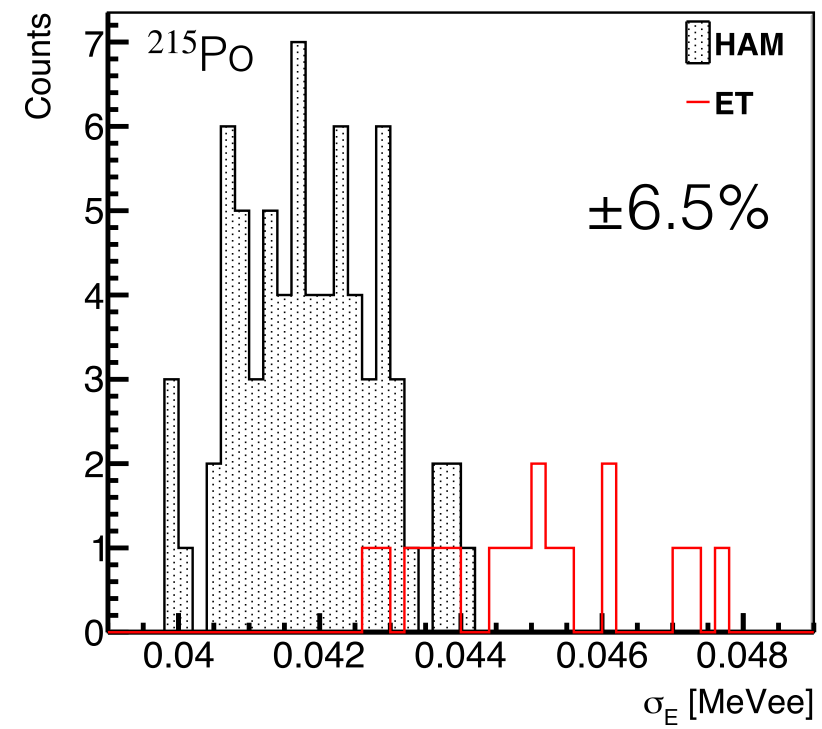
Bonus!

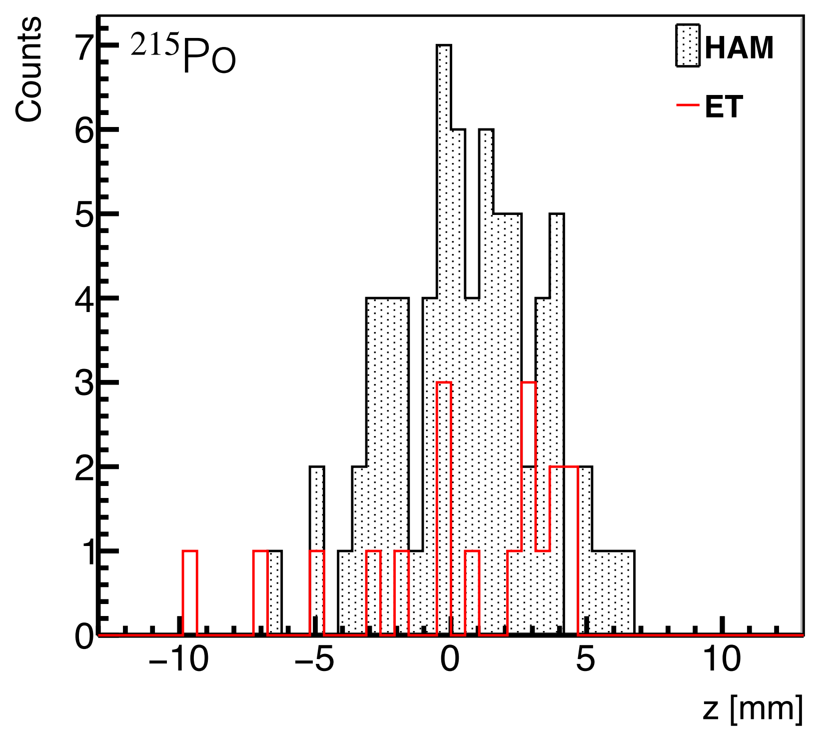


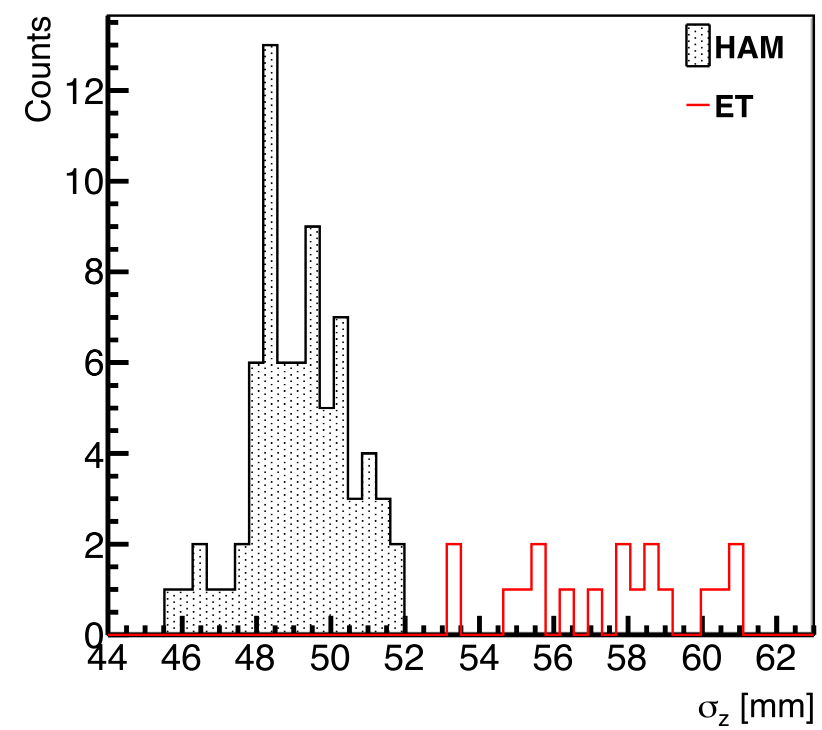








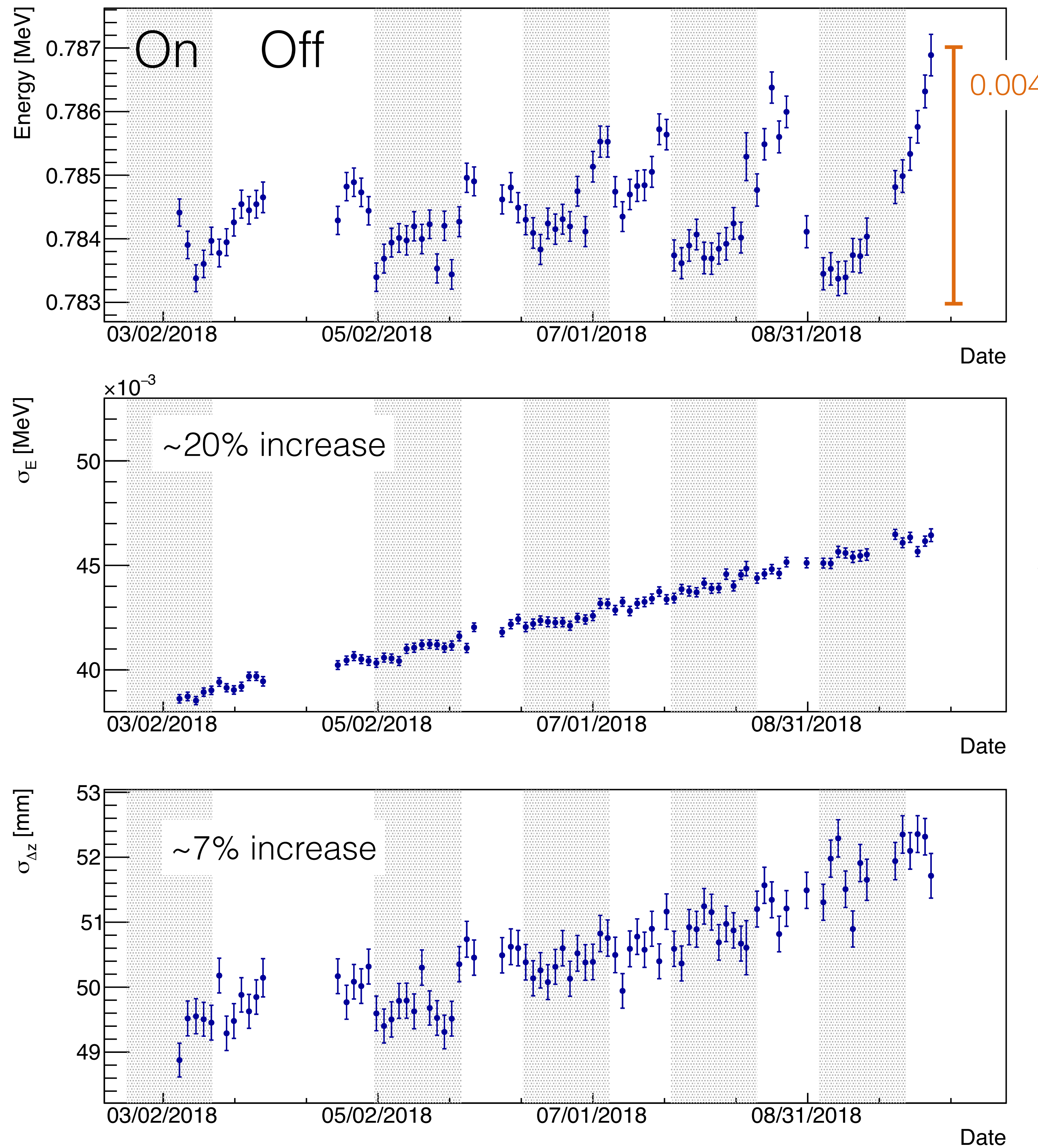




Position and Energy Resolution of Alphas

Bonus!

~7 months

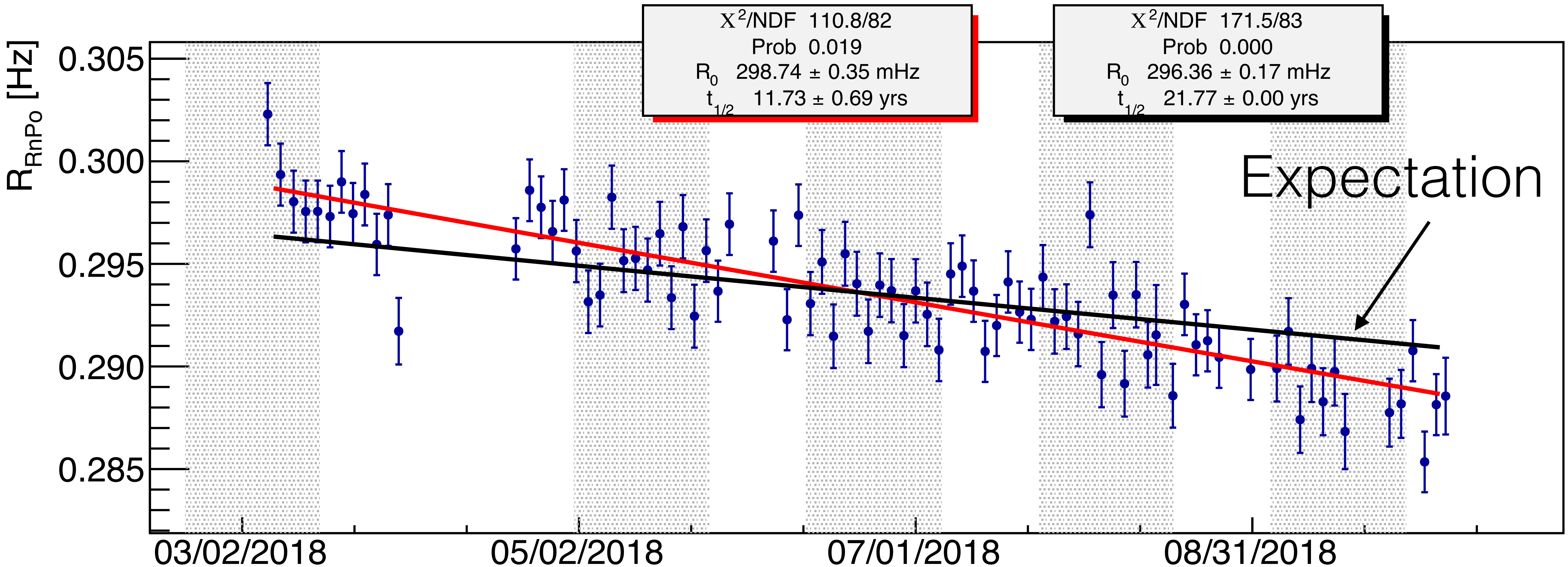


^{215}Po Energy Mean

^{215}Po Energy Width

Δz width

^{227}Ac Rate Versus Time

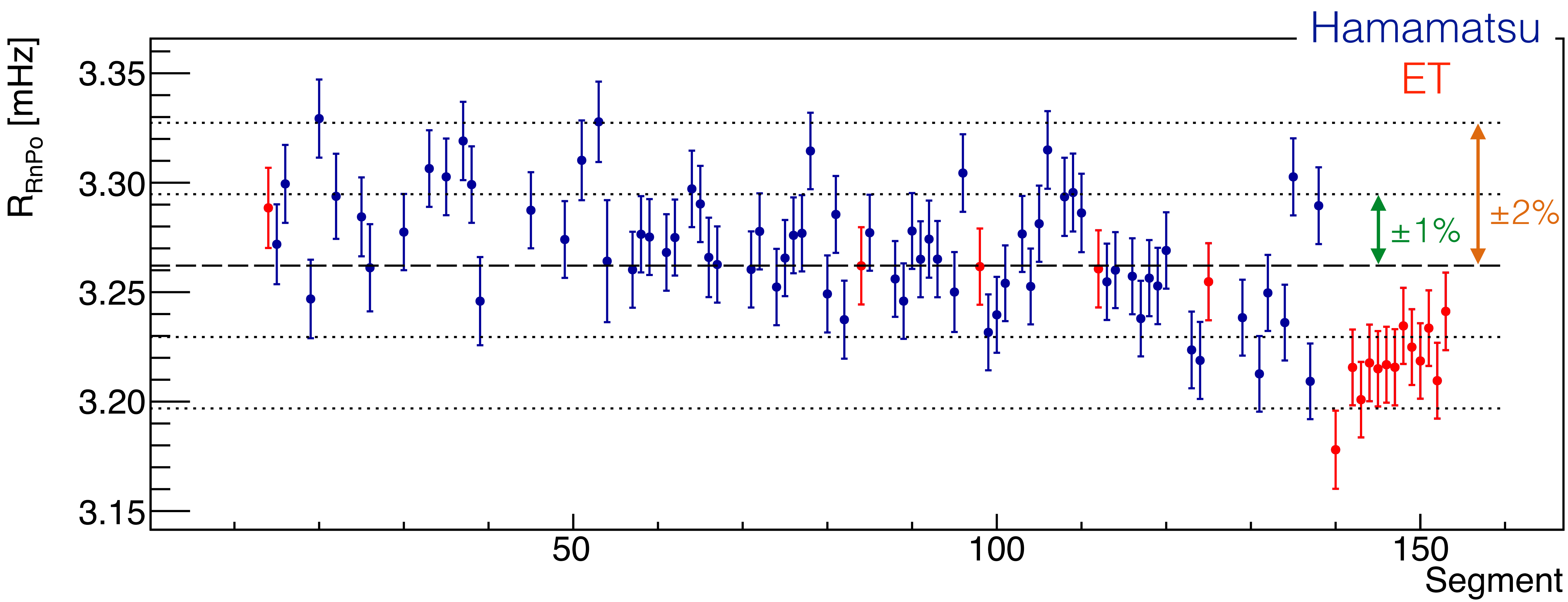


Decaying 1.56 ± 0.21% faster than expectation over 7 months

Is ^{227}Ac falling out of the scintillator? Is it adsorbing?

^{227}Ac Rate Per Segment

Average = 3.262 ± 0.002 mHz



Statistical errors ~0.6 %

standard deviation of Hamamatsu segments = 0.026 mHz

Systematic Errors

- **±1%:** ^{227}Ac decay rate falling faster than expectation
  - see slide 19
- **±0.15%:** energy, PSD, and dz cuts
  - Efficiency calculations assume Gaussian distributions
  - How does the rate depend on the width of these cuts in simulation and data?
- **±0.22%:** contamination from other alpha coincidence sources
  - Using timing and position information can calculate rate of contamination in RnPo data selection

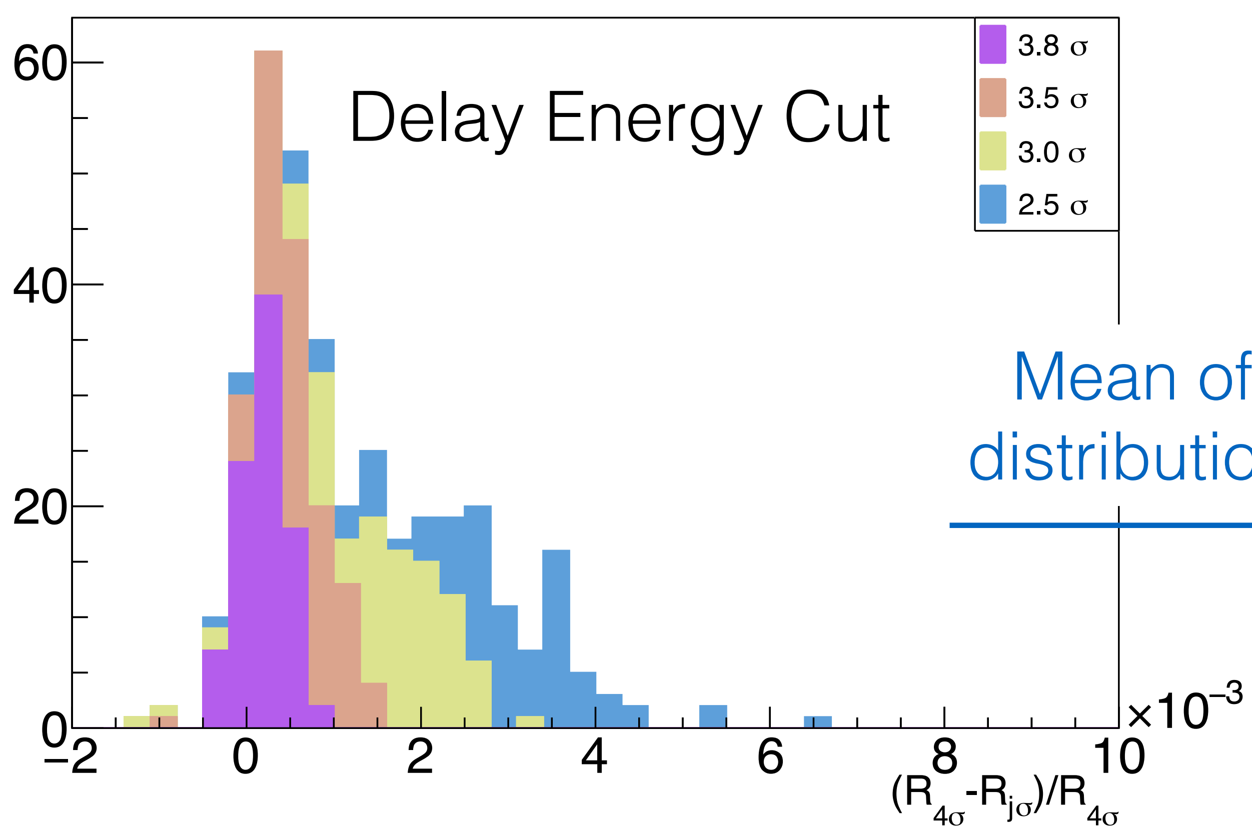
Systematic Error: Cuts

Cut efficiencies are calculated by fitting the energy, PSD, and dz distributions with Gaussians. This assumes that they all are true Gaussian shapes.

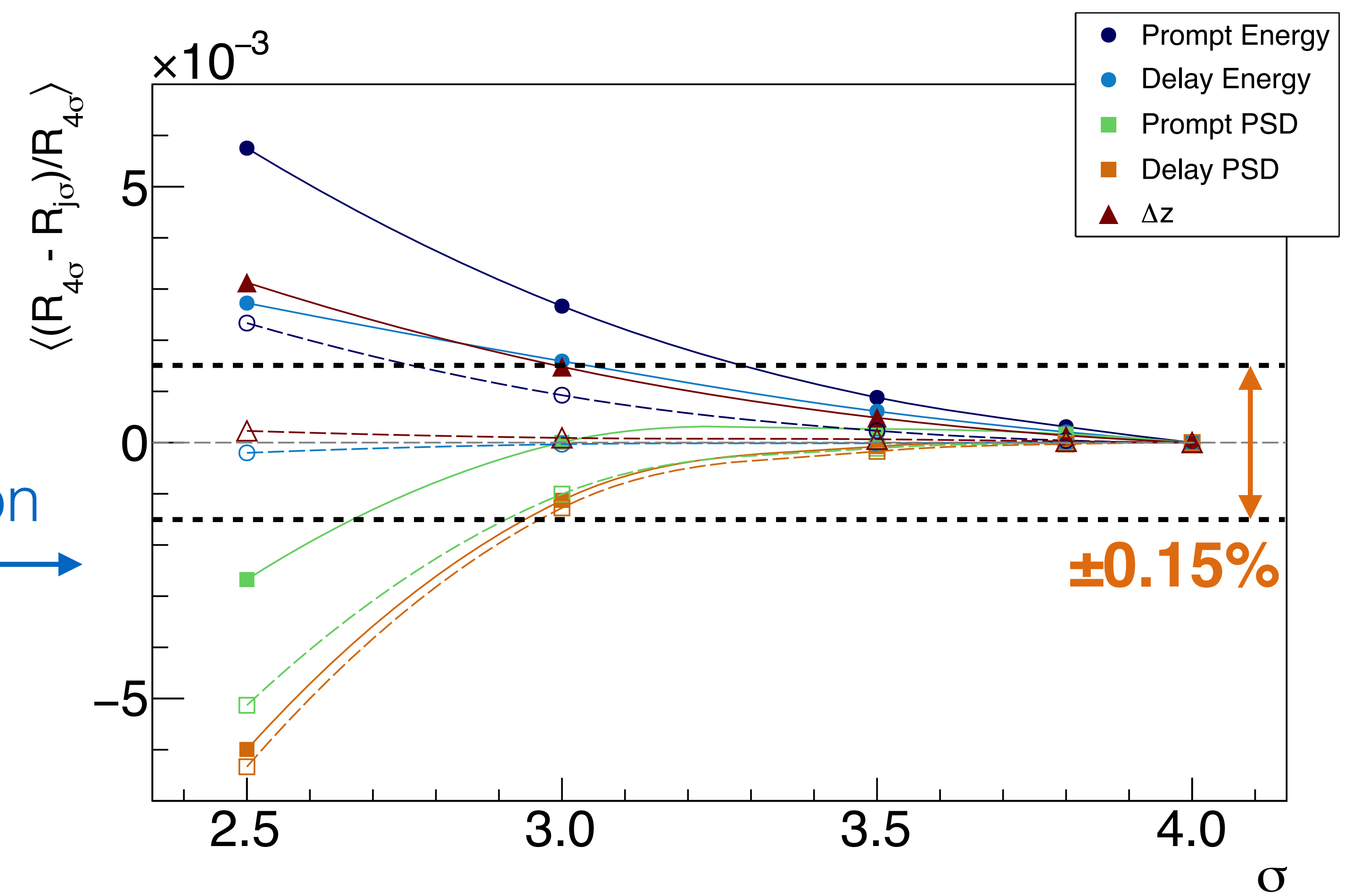
For each segment calculate:

$$\frac{R_{4\sigma} - R_{i\sigma}}{R_{4\sigma}}$$

Distribution



Mean of distribution



Systematic Error: Other Alpha Contamination

$$^{220}\mathrm{Rn} \rightarrow {}^{216}\mathrm{Po} + \alpha \rightarrow {}^{212}\mathrm{Pb} + \alpha$$ from naturally occurring ^{232}Th

$$^{223}\mathrm{Ra} \rightarrow {}^{219}\mathrm{Rn} + \alpha \rightarrow {}^{215}\mathrm{Po} + \alpha \rightarrow {}^{211}\mathrm{Pb} + \alpha$$ triple α from ^{227}Ac chain

^{219}Rn (^{215}Po) Energy Range is 0.48 (0.61) - 1.18 $\mathrm{MeV_{ee}}$

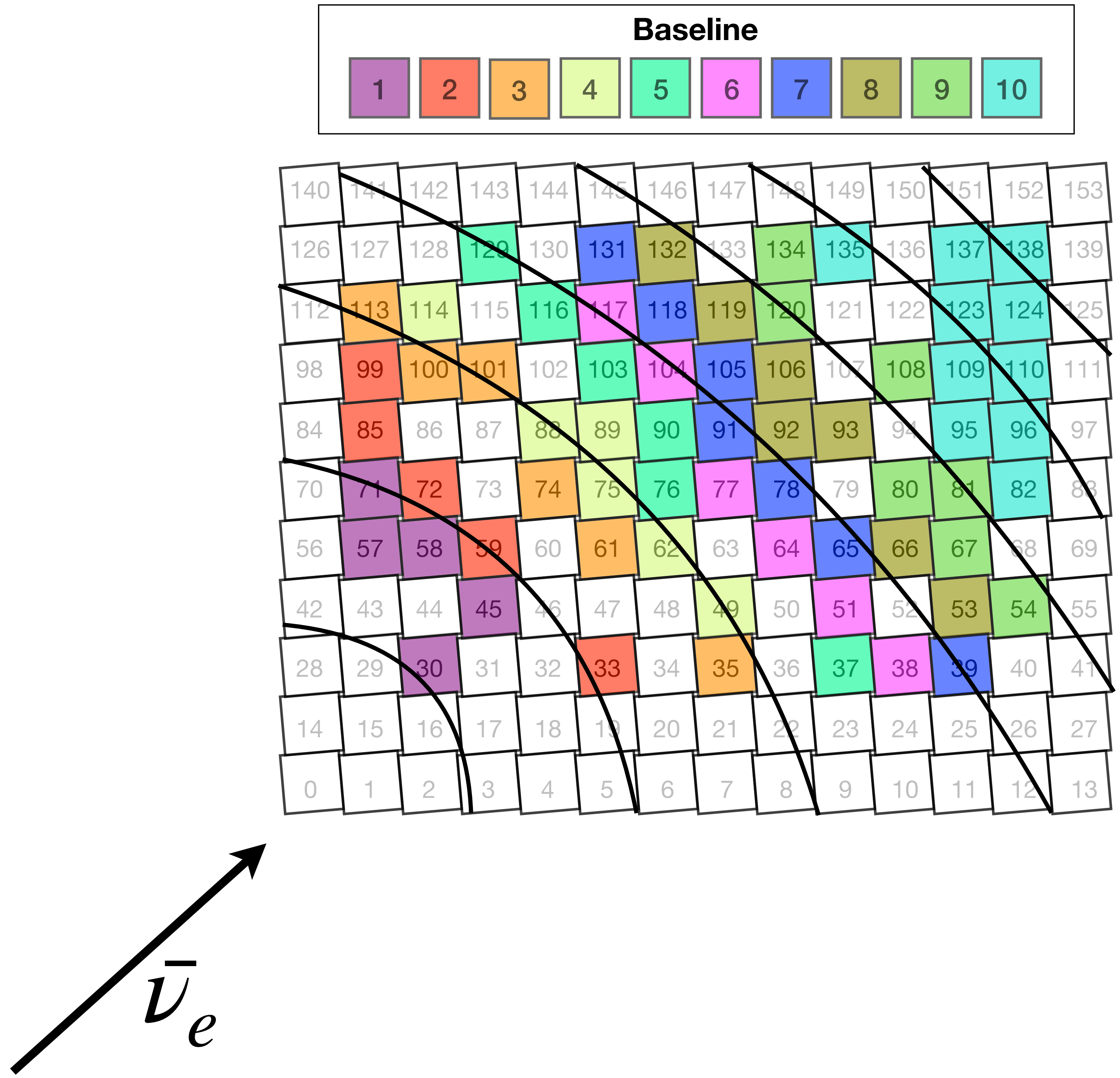
Isotope	$t_{1/2}$ [ms]	E [MeV]	QE [MeVee]	1σ width [MeVee] (5% res.)
^{220}Rn	55600	6.2881	0.5942	0.0412
^{216}Po	145	6.7783	0.6776	0.0412
^{223}Ra	9.88×10^{8}	5.7162	0.5031	0.0355
^{219}Rn	3860	6.8191	0.6847	0.0414
^{215}Po	1.781	7.3861	0.7876	0.0444

Prompt	Delay	$t_{1/2}$ [ms]	Energy Cut Eff.	Time Cut Eff.	Rate [mHz]*	
^{220}Rn	^{216}Po	145	0.925	0.0066	0.52	**0.22%**
^{223}Ra	^{219}Rn	3860	0.815	0.000010	0.0021	0.00083%

*Assuming an 227Ac rate of 240 mHz

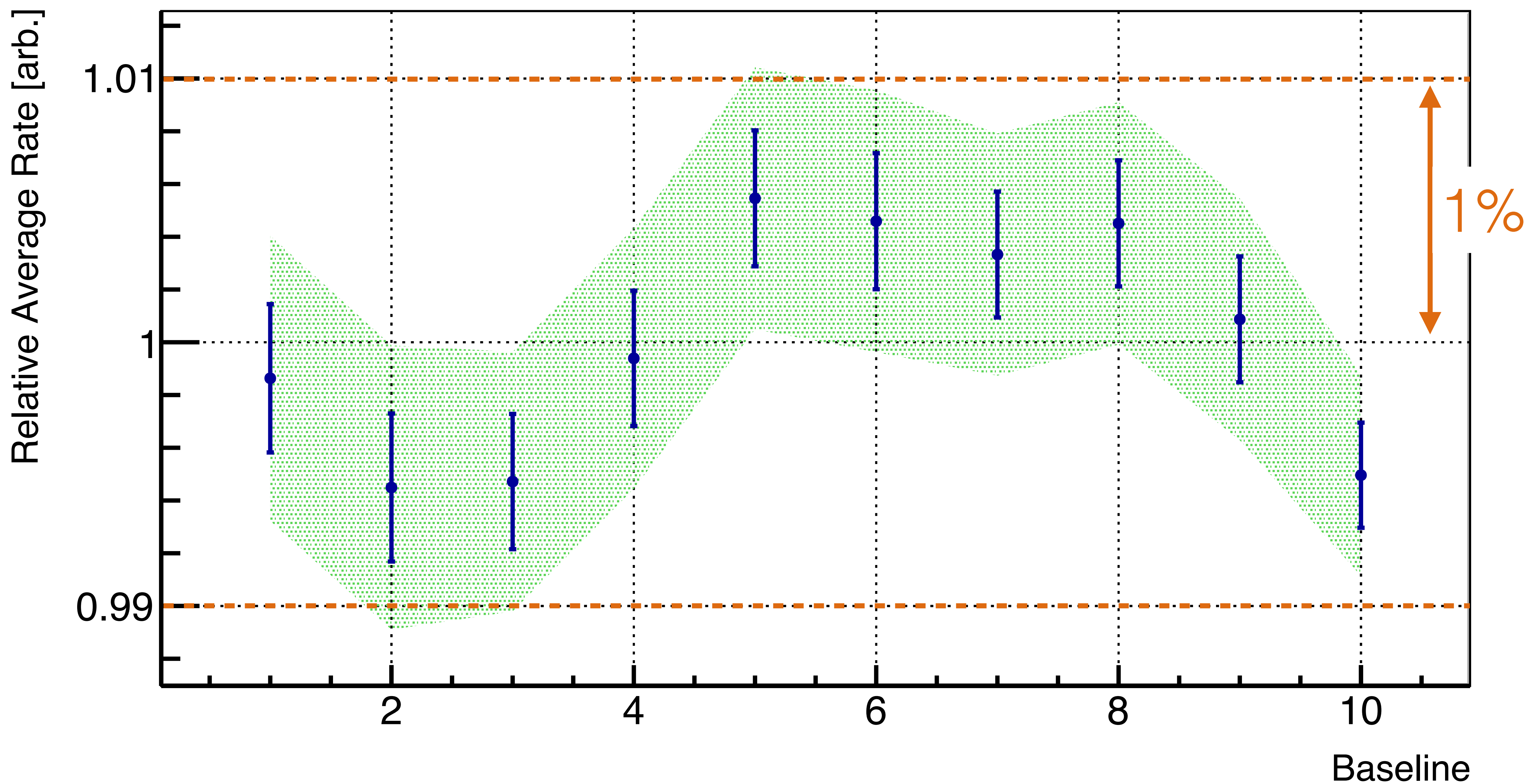
^{227}Ac Rates to Volume Variations

Calculate average ^{227}Ac rate per baseline



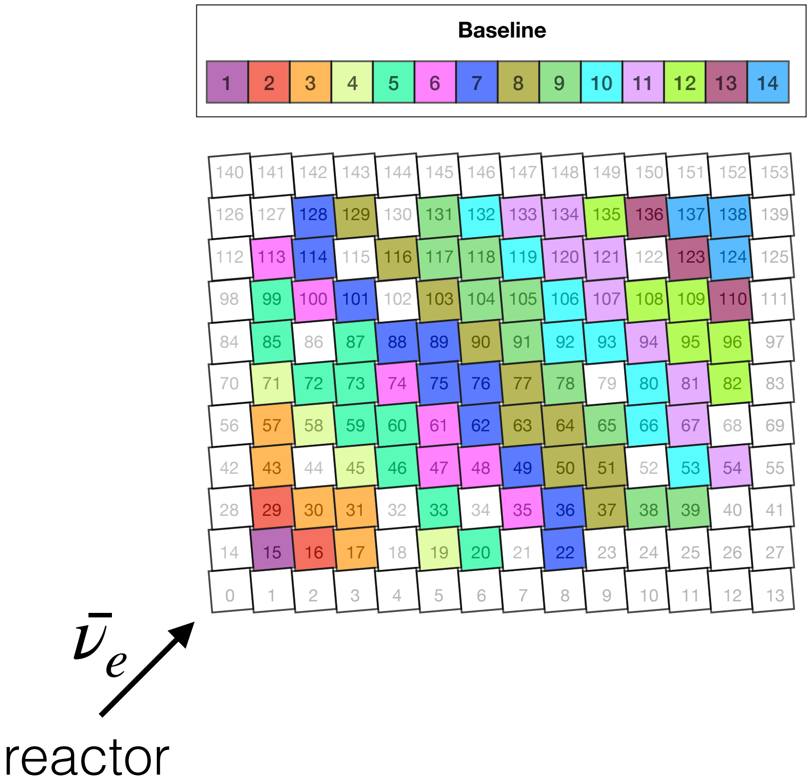
reactor

^{227}Ac Rate Per Baseline



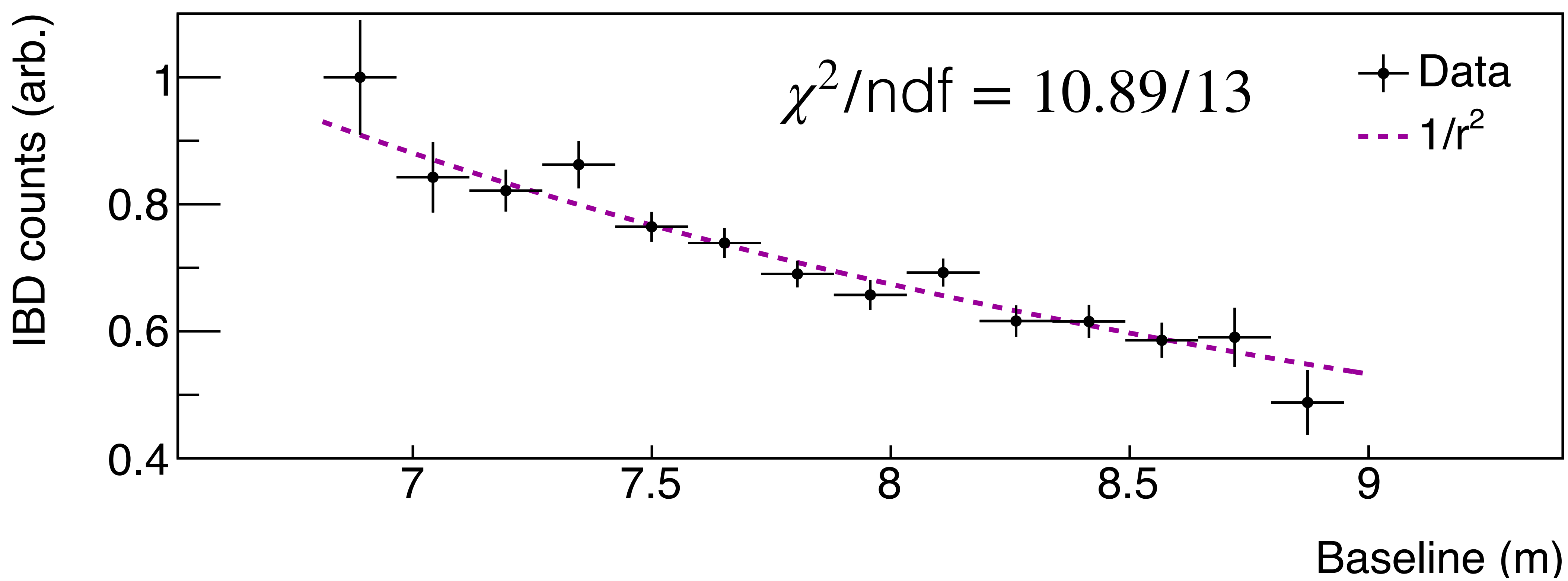
< 1% volume variation over baselines

^{227}Ac Rate Per Baseline

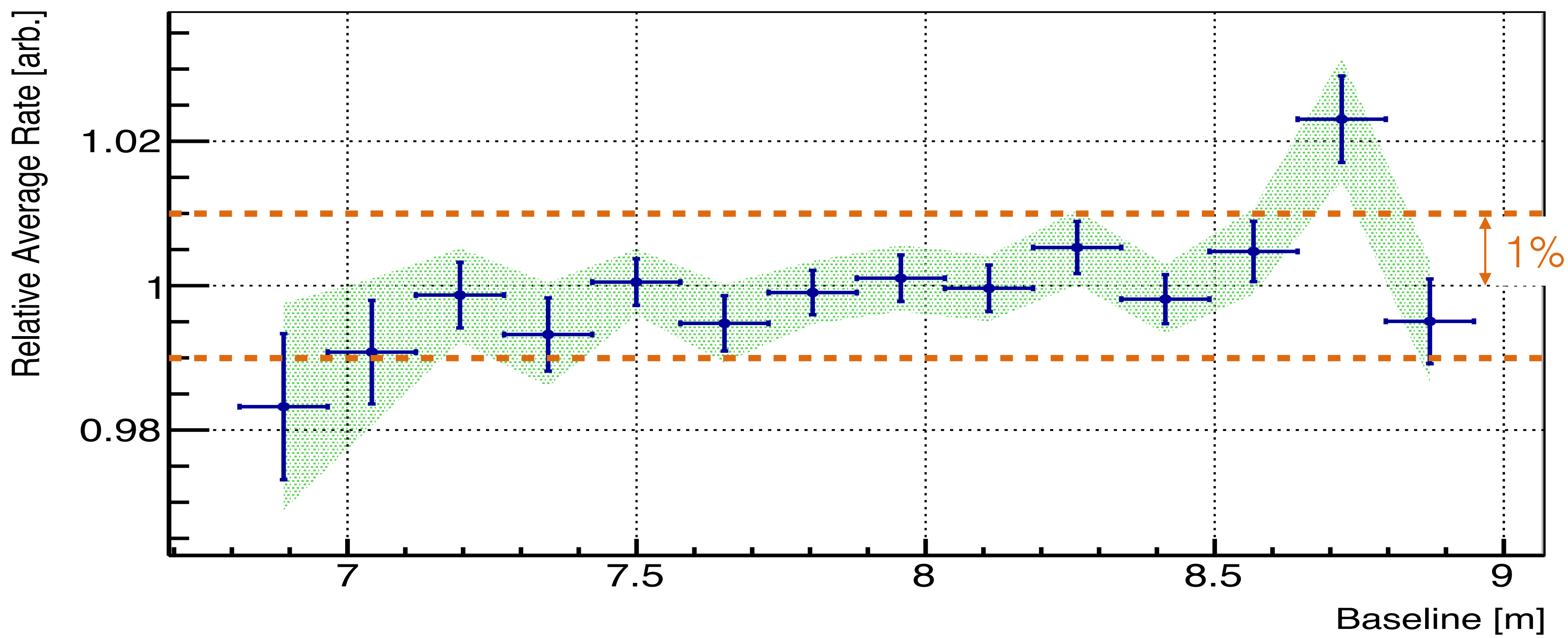


Same procedure for published data set.

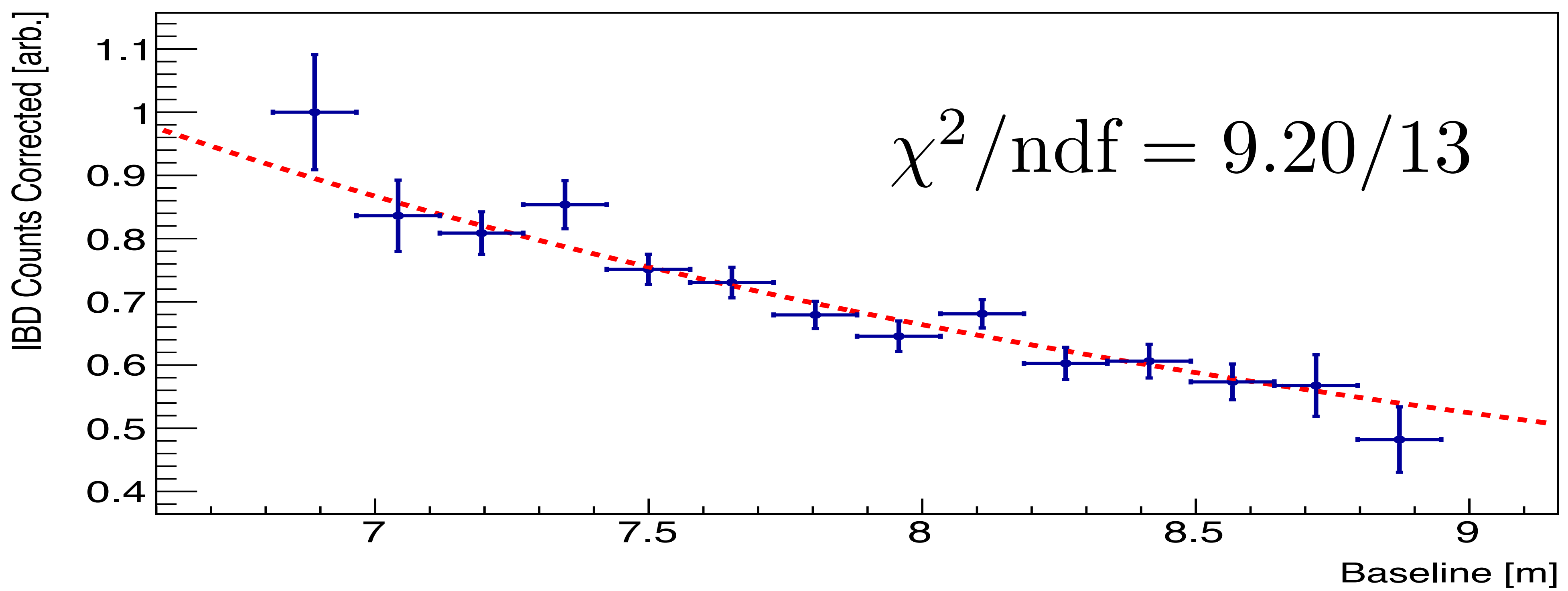
Apply corrections to IBD rate versus baseline



^{227}Ac Rate Per Baseline



~2% volume variation over baselines.
5% error was included in oscillation analysis.



Better chi-squared!

Conclusion

- I have proven that spiking the liquid scintillator with ^{227}Ac is a viable method for measuring volume variations

- This is useful for a dataset with more statistics, in which volume could become a systematic error

- For current PROSPECT datasets this is useful for placing limits on volume variation errors used in the oscillation analysis

- ^{227}Ac has also proven useful as a stability metric

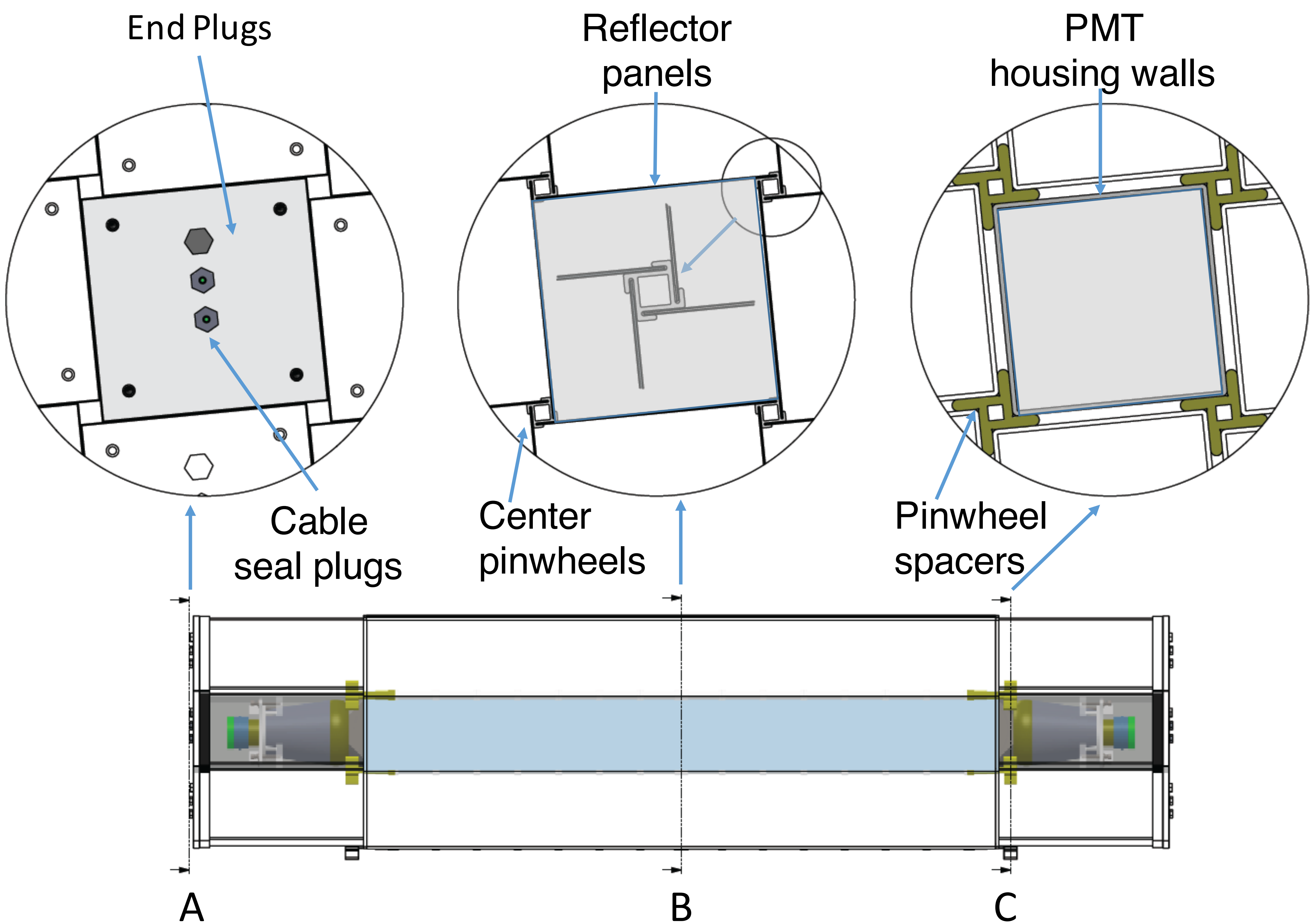
Thanks!

Temple Team

Jim N.
Don J.
Adam H.
James W.

Backup

PROSPECT Segment



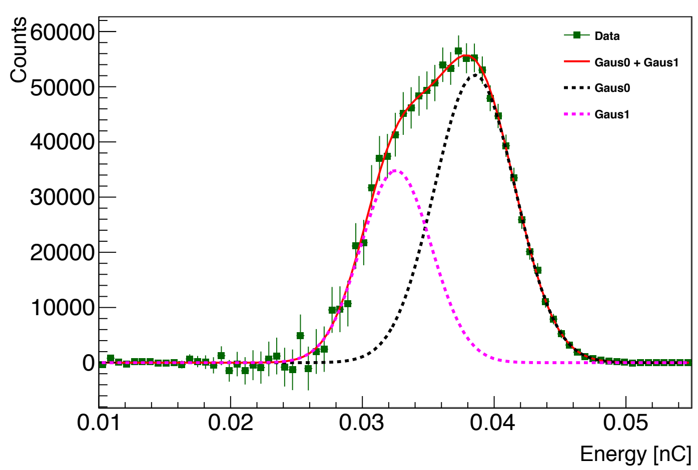
PROSPECT Row Assembly

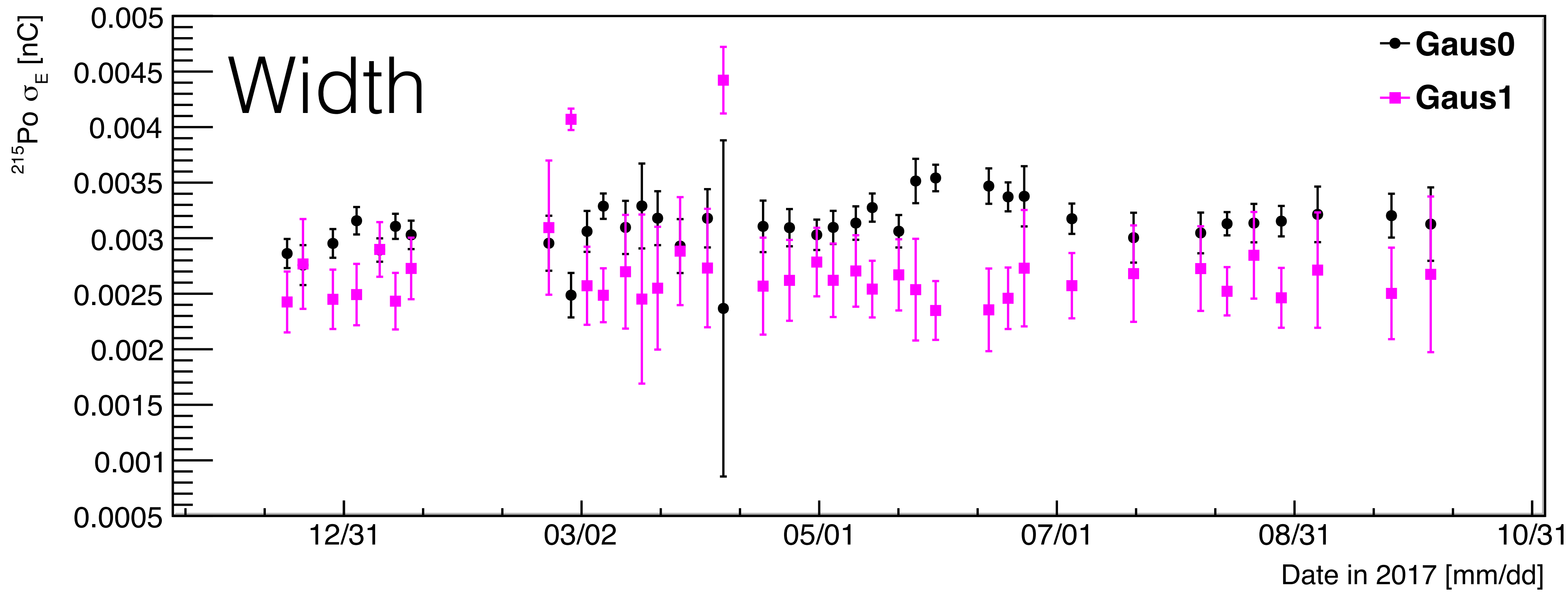
Material Studies

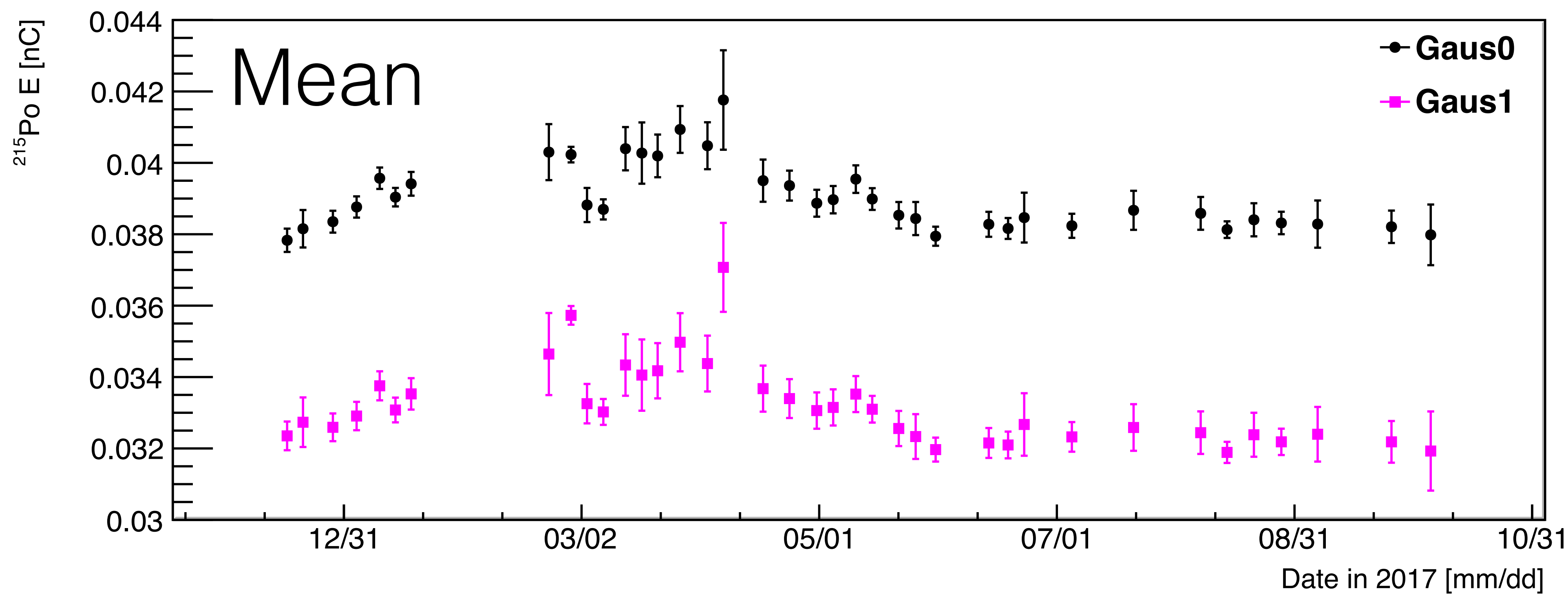
Material	Detector Use	Sample Size
UVT Acrylic	Front window of PMT housing	$1.0 \times 1.15 \times 0.1$ cm^3
FEP	Film on optical separators	1.5×1.5 cm^2, 3 mm thick
PLA	3D printed pinwheels	10 disks; 0.5 cm diameter, 0.1 cm thick
PEEK	Seal plugs through which the high voltage and signal cables were threaded. Screws used to bolt together segment supports. Spacers at the base of the acrylic tank.	1 Nut; ID 0.5 cm, small OD 1cm, large OD 1.1cm, thickness 0.5 cm
RG188 Cable	High voltage and signal cables	4.5" long
Viton O-ring	Seal back plugs of PMT housings and seal acrylic tank	10 O-rings; OD 6mm, ID 3mm, thickness 1.5mm

Table 5.2: Samples used to test if ^{227}Ac or its daughters would adsorb onto detector materials.

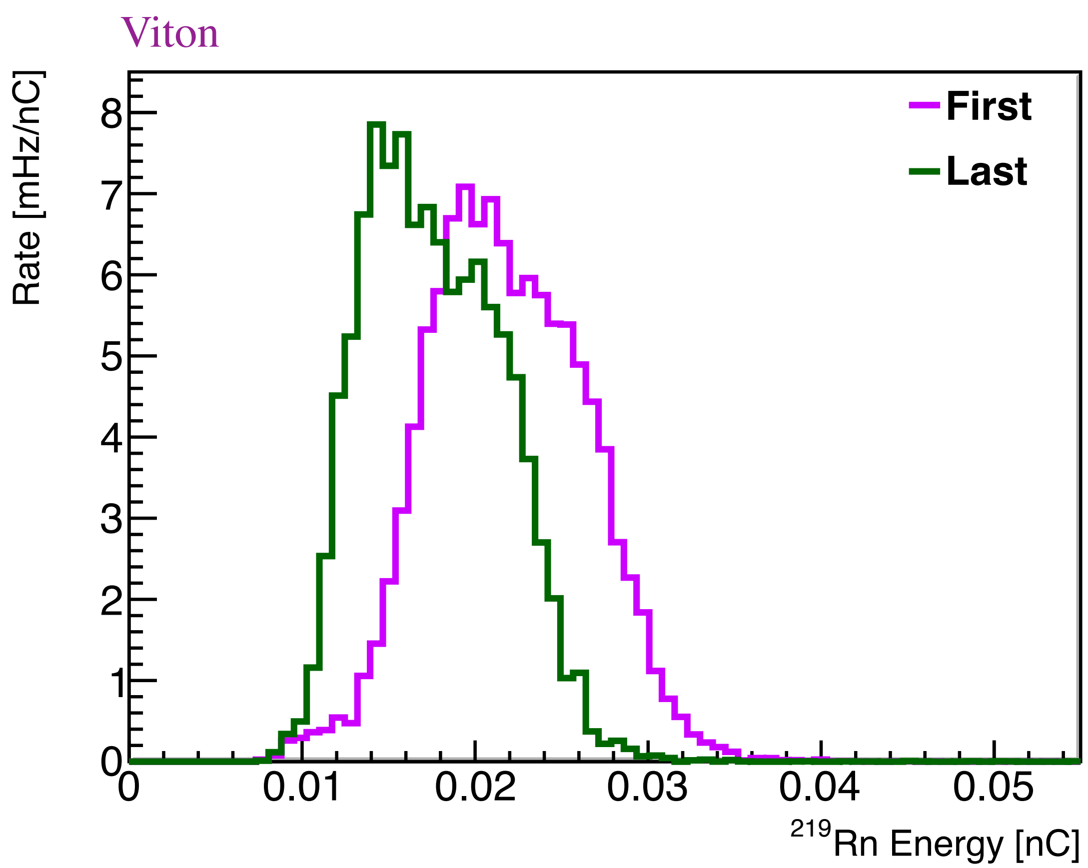
Material Studies - ^{215}Po Energy

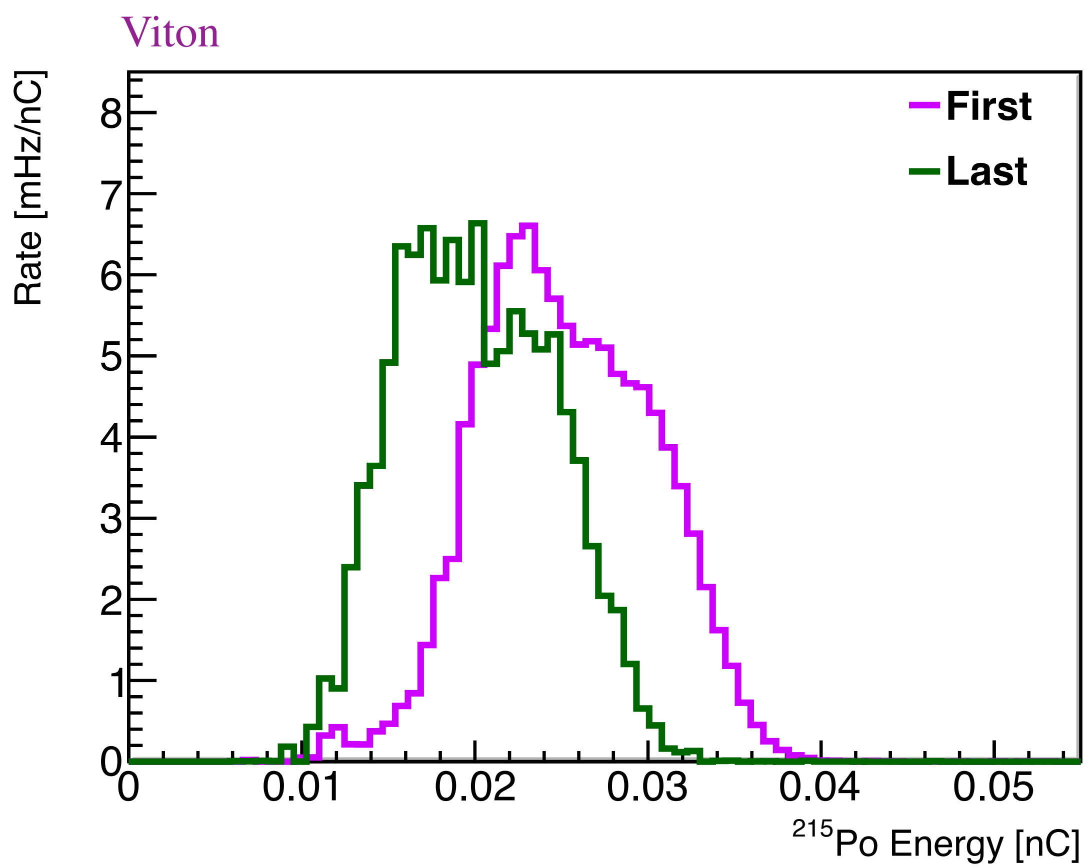


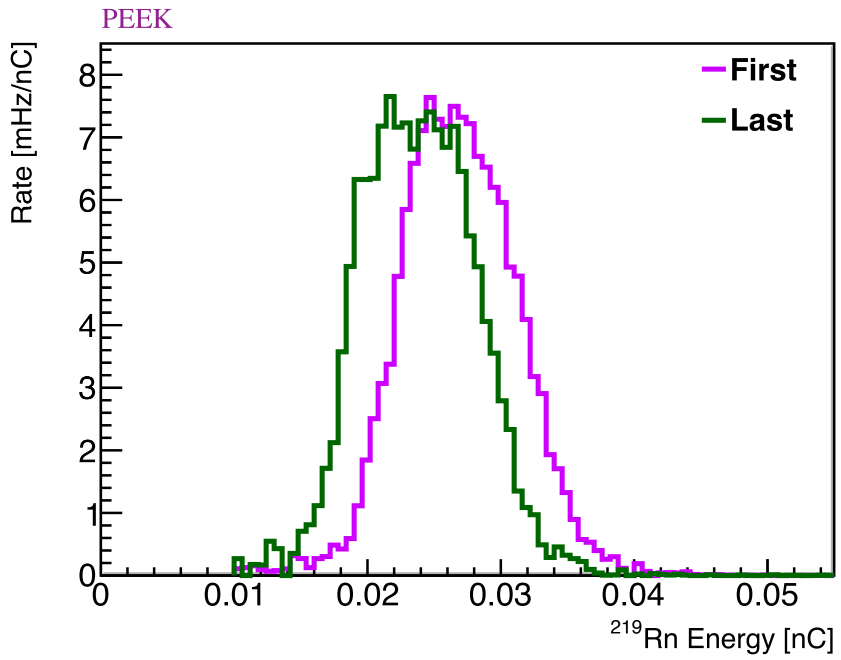


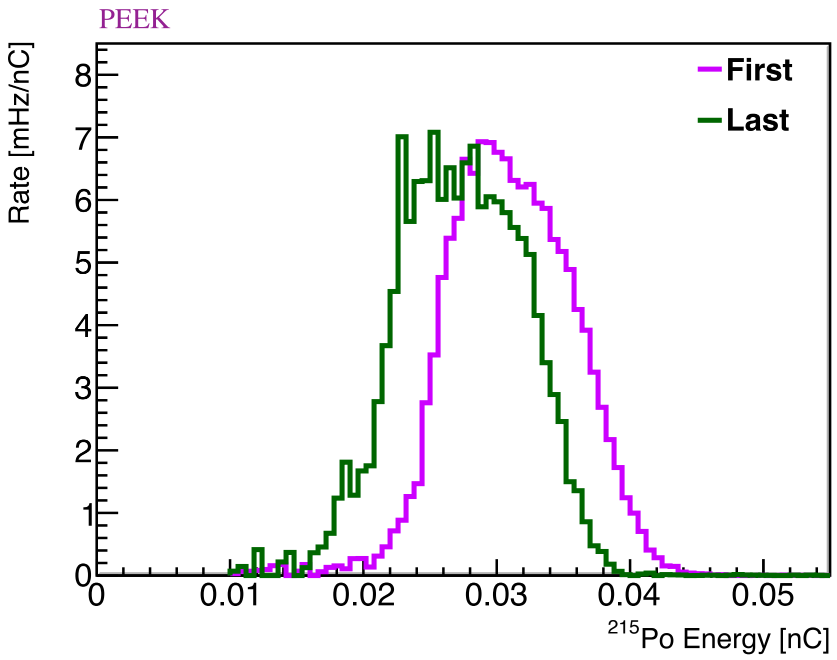


Material Studies - Viton

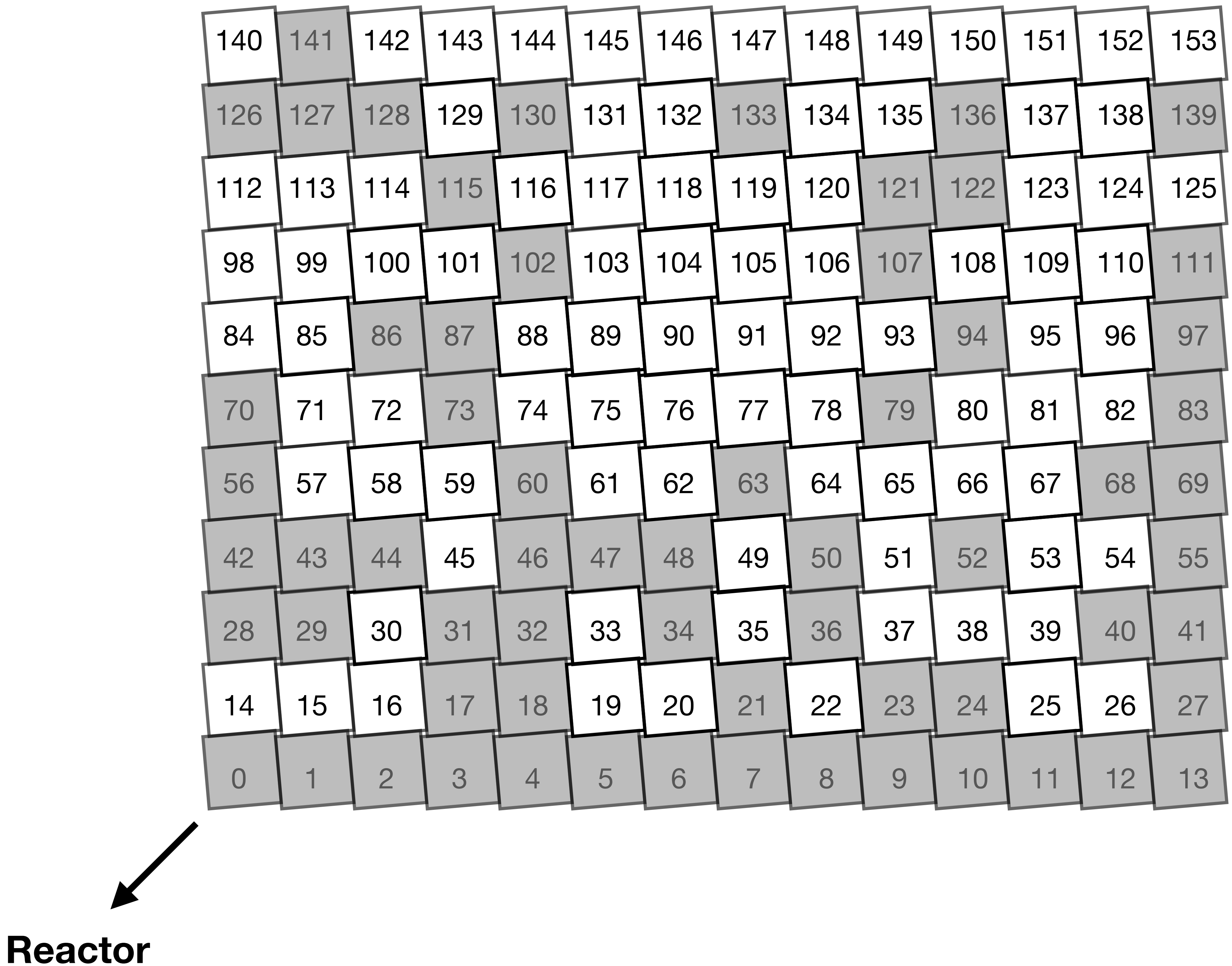






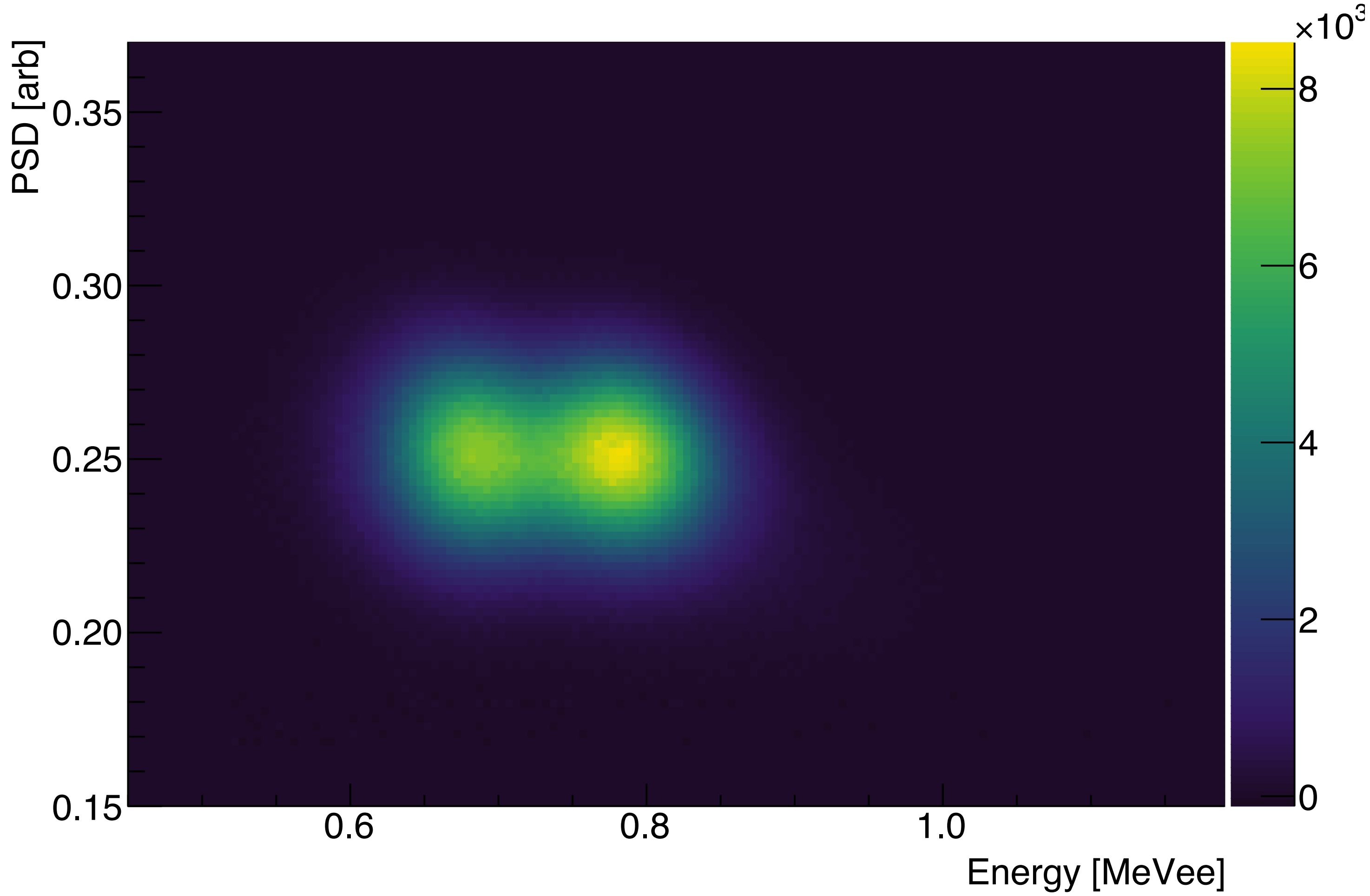


Excluded Segments

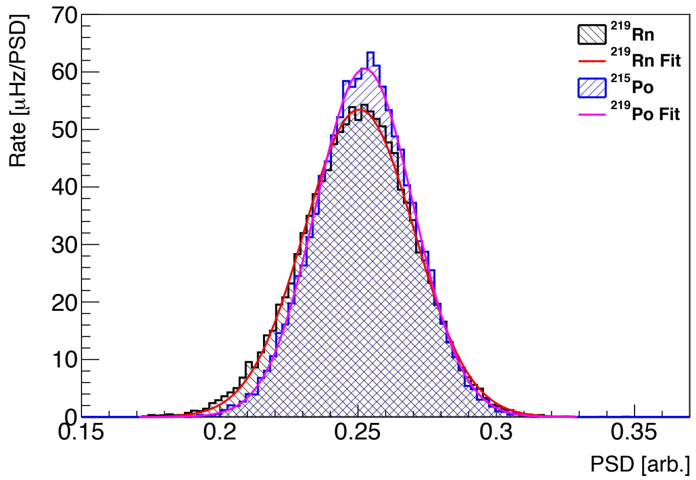


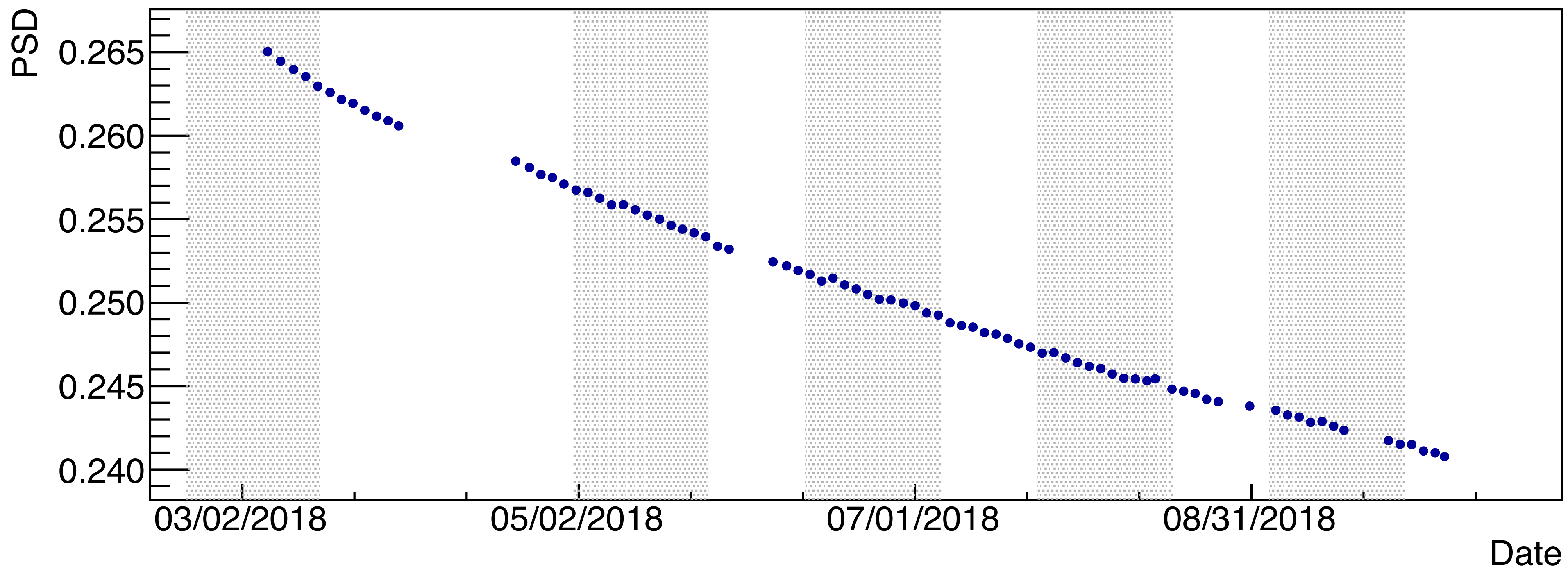
^{227}Ac Broad Cuts

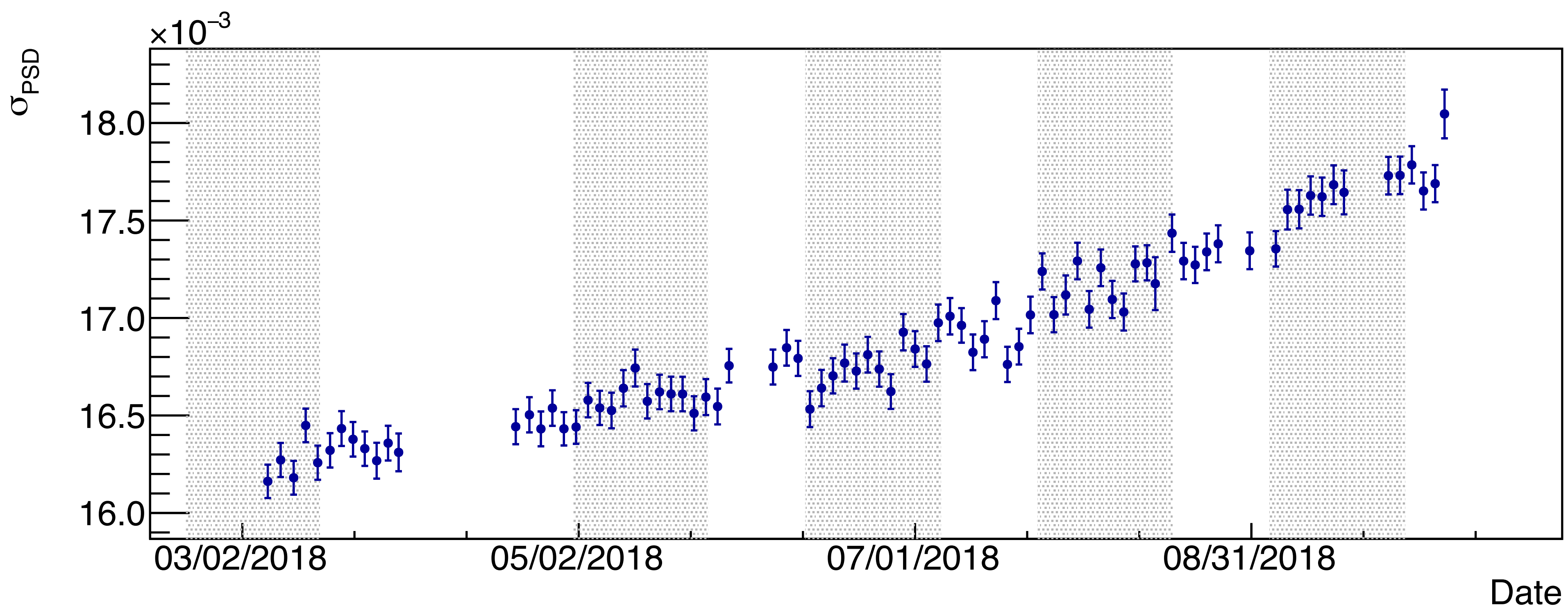
Prompt Energy	$0.48 < \mathrm{E} < 1.18$ MeVee
Delay Energy	$0.61 < \mathrm{E} < 1.18$ MeVee
PSD	$0.16 < \mathrm{PSD} < 0.36$
$\Delta z = \lvert z_{\mathrm{delay}} - z_{\mathrm{prompt}} \rvert$	$\Delta z < 250$ mm
$\Delta t = t_{\mathrm{delay}} - t_{\mathrm{prompt}}$	$\Delta t < 5\tau$ ms



^{215}Po PSD vs Time





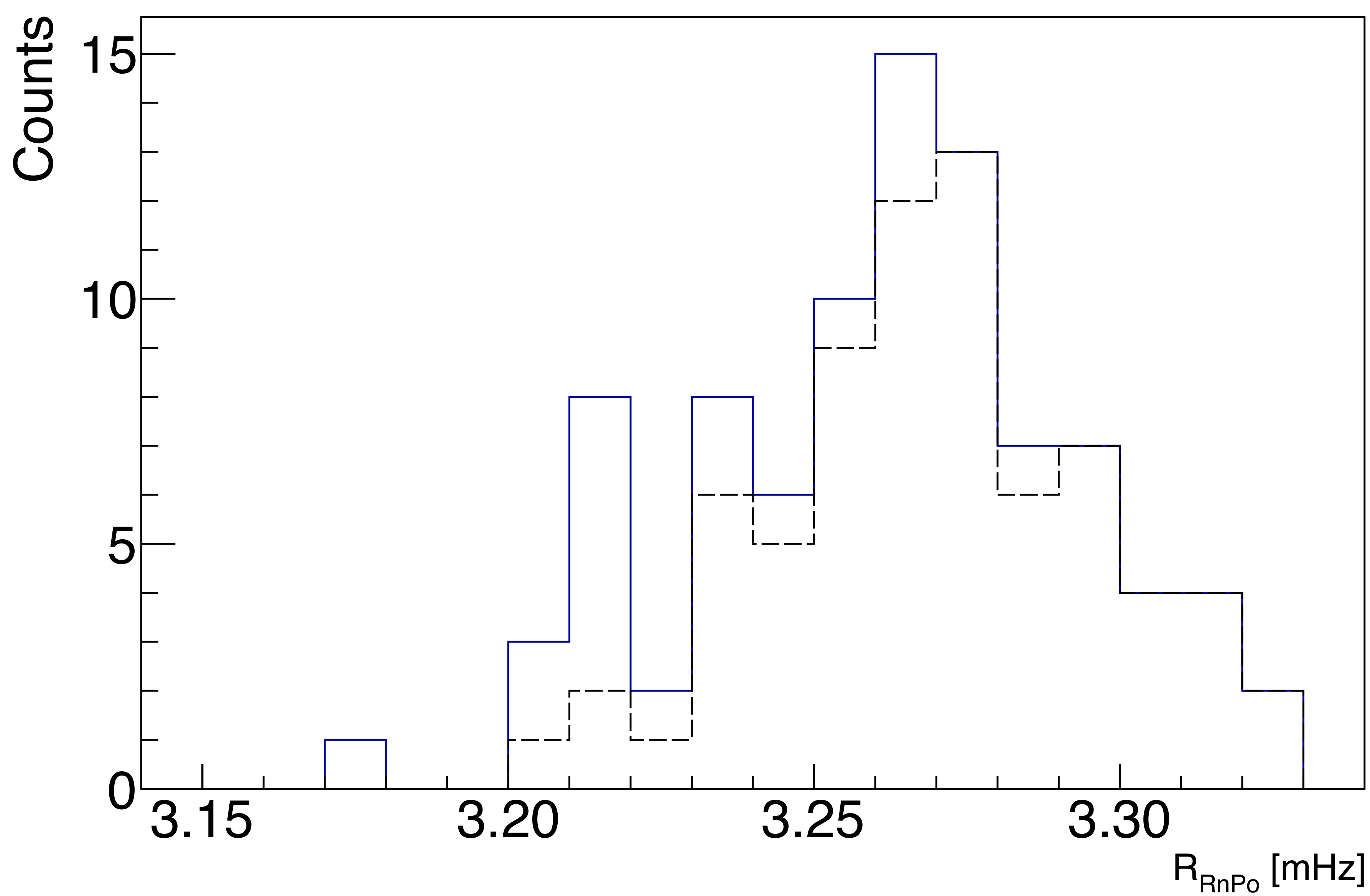


RnPo Cuts

Cut	Range	$\langle \mathrm{Eff_{Cell}} \rangle$%	$\langle \mathrm{Eff_{Time}} \rangle$%
Pileup veto	Veto any cluster preceded less than 800 ns by another cluster		
PSD	$\mu - 4\sigma < \mathrm{PSD_{Rn}} < 0.36$	99.993	99.996
	$\mu - 4\sigma < \mathrm{PSD_{Po}} < 0.36$	99.994	99.997
Energy	$\mu - 4\sigma < \mathrm{E_{Rn}} < 1.18$ MeV	99.997	99.996
	$\mu - 4\sigma < \mathrm{E_{Po}} < 1.18$ MeV	99.996	99.996
Position	$-1000 < \mathrm{z_{Rn/Po}} < 1000$ mm		
	Segment-Rn = Segment-Po		
Δz	$\mu - 4\sigma < \Delta z < \mu + 4\sigma$	99.994	99.993
Δt	$0.5 < \Delta t < 12.845$ ms		

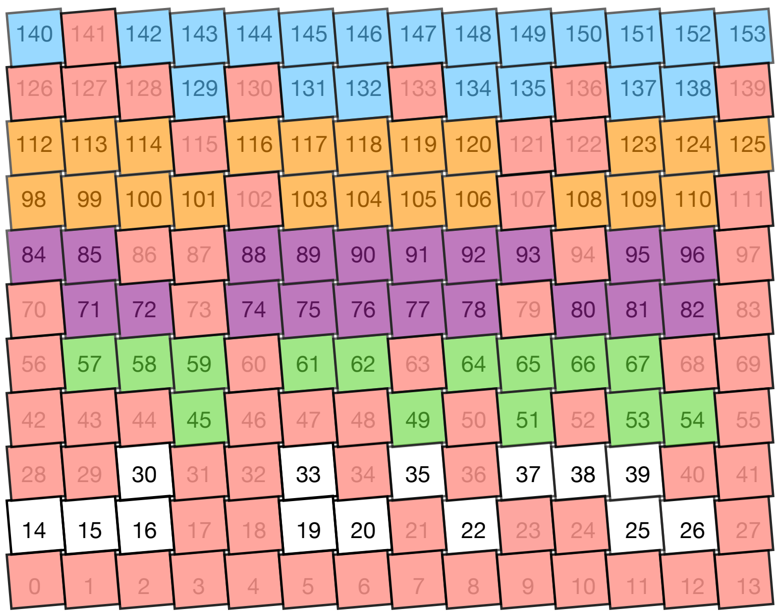
Table 5.10: Summary of the chosen cuts and their average efficiencies for determining the ^{227}Ac rate in the PROSPECT AD. The means and sigmas are determined by fitting the peaks of all distributions with Gaussians. They are found for each individual segment or each individual time bin (depending on the analysis being done). Average efficiencies are found by fitting the data in Figures 5.26 and 5.27 with constants.

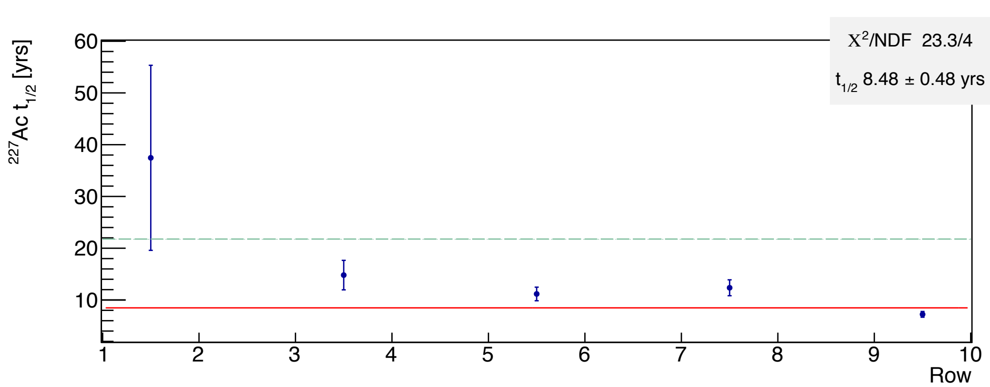
Rate Per Segment

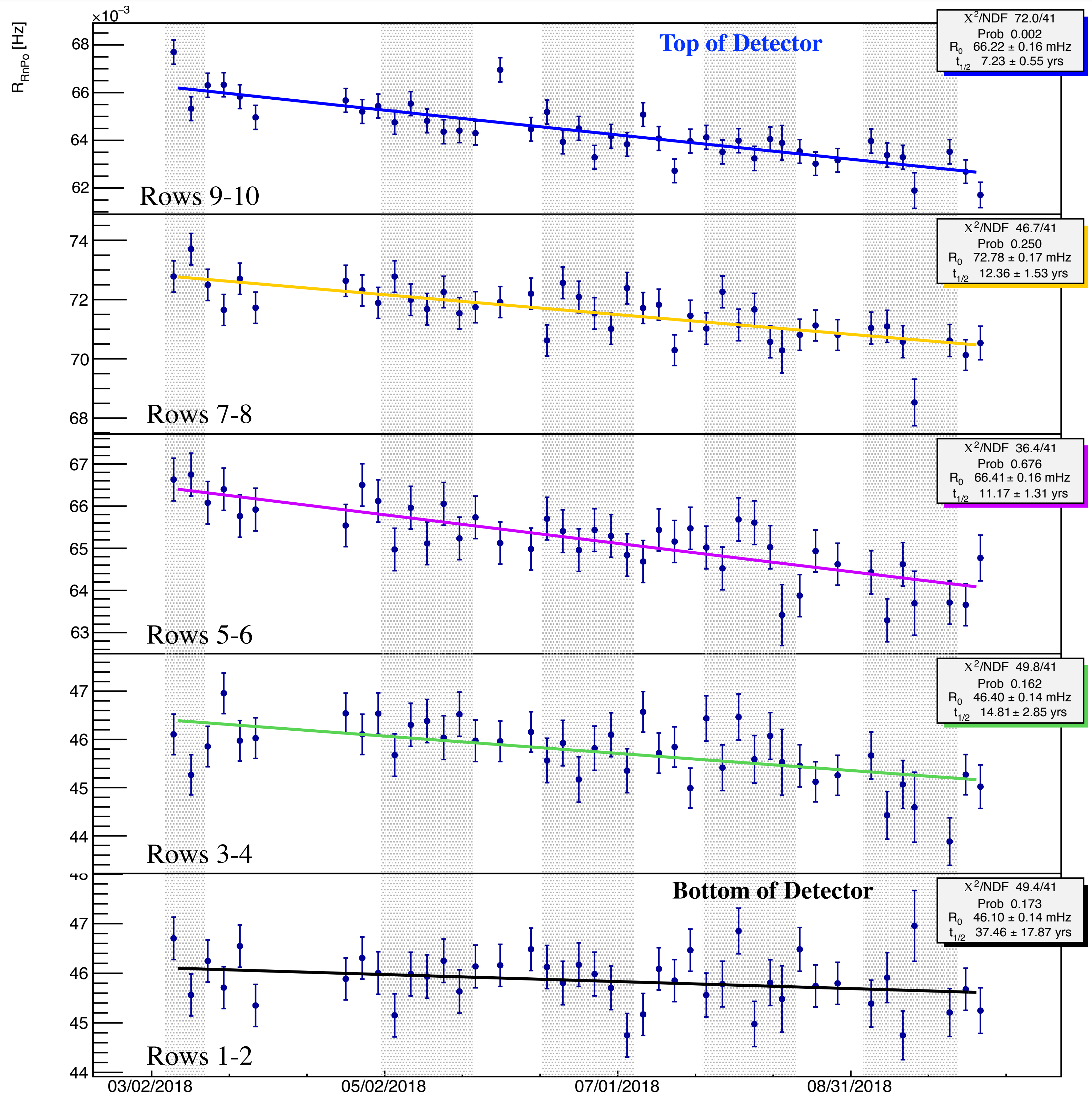


std dev = 0.031 mHz for all
std dev = 0.026 mHz for Ham

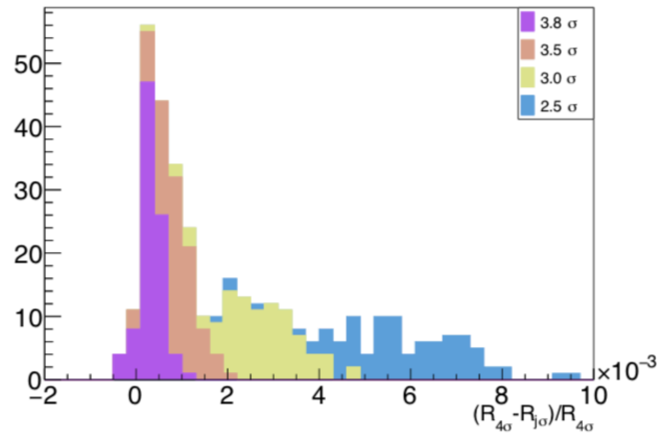
227Ac Rate vs Row



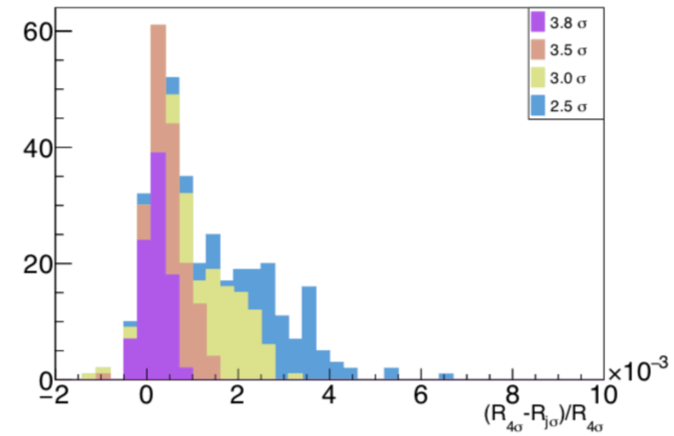




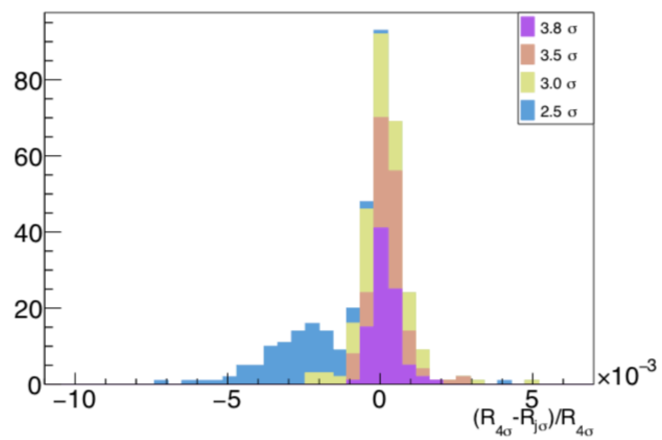
Systematic Error: Cuts



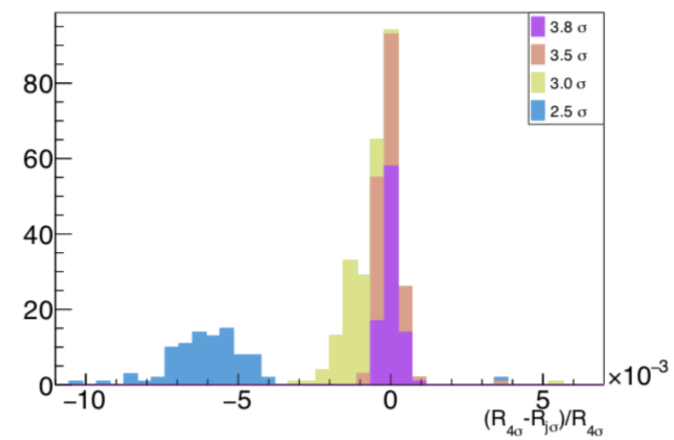
(a) Prompt Energy



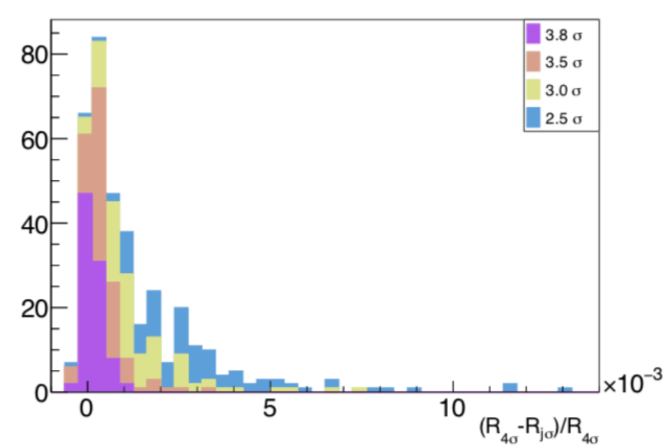
(b) Delay Energy



(c) Prompt PSD

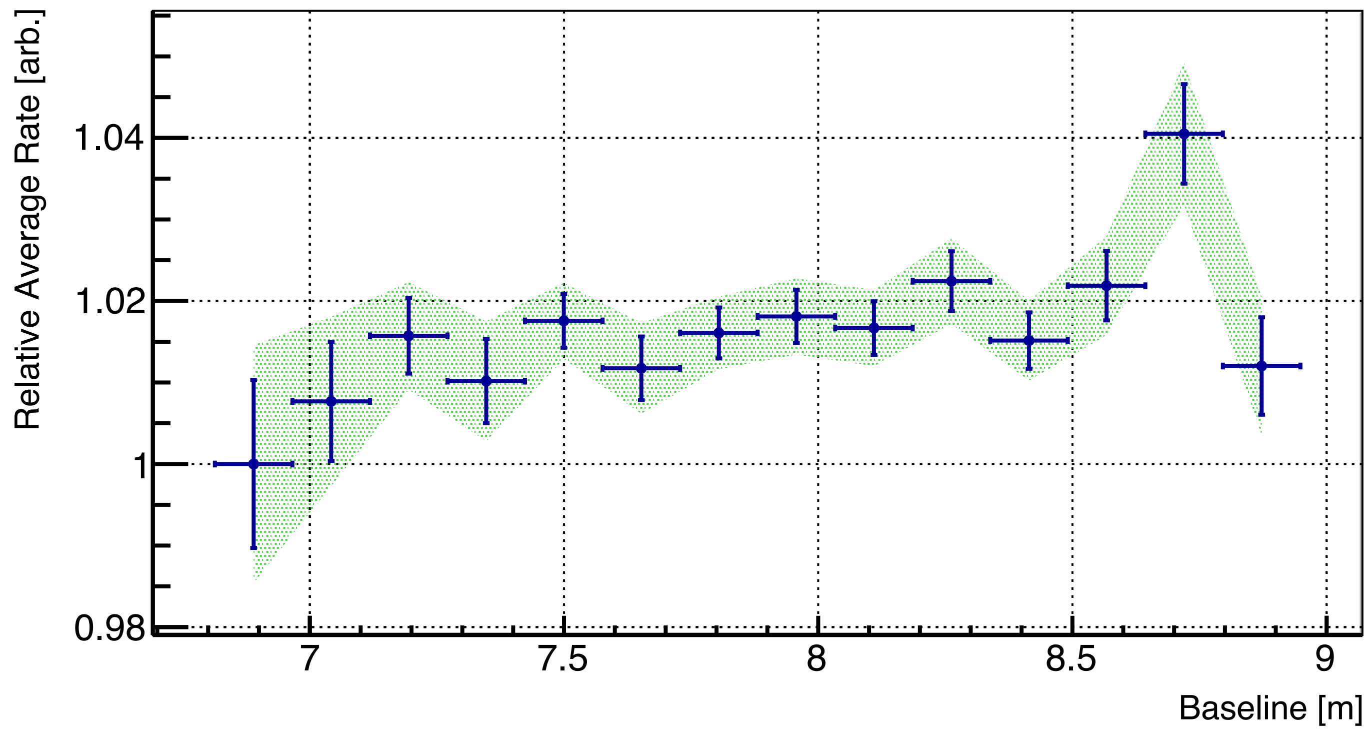


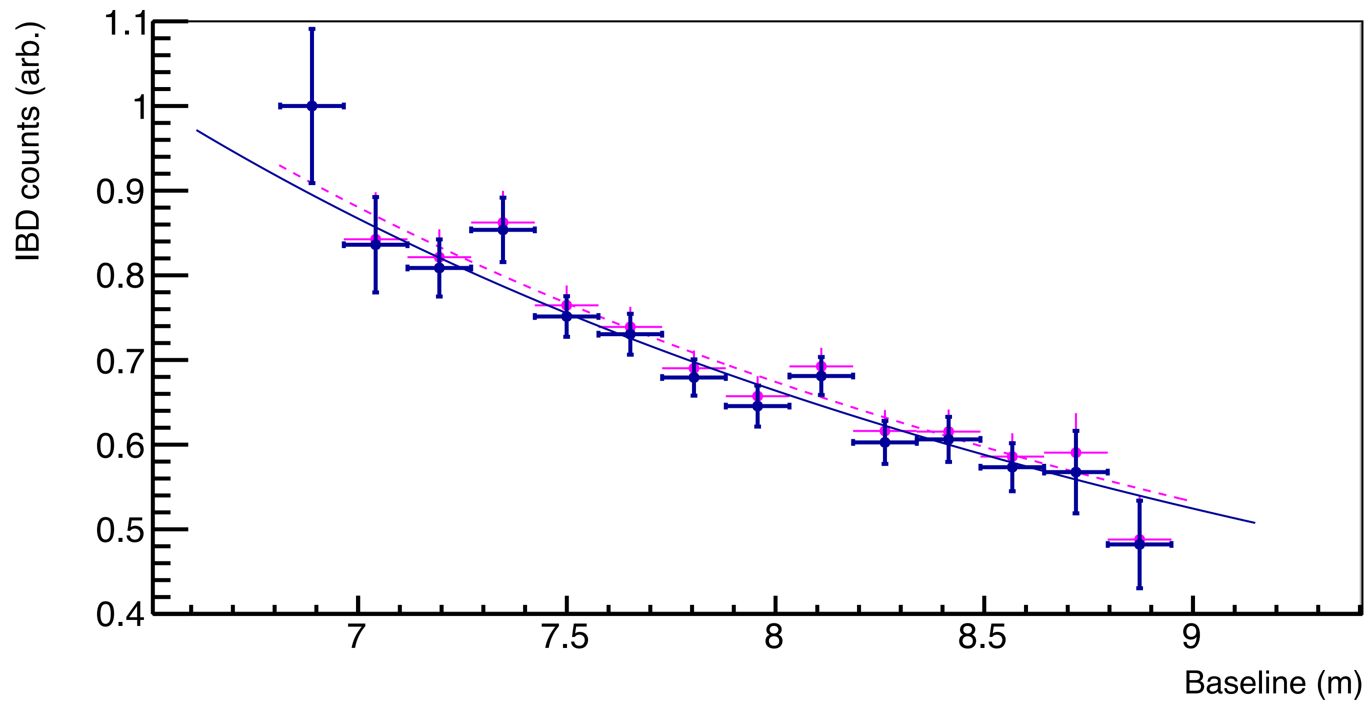
(d) Delay PSD



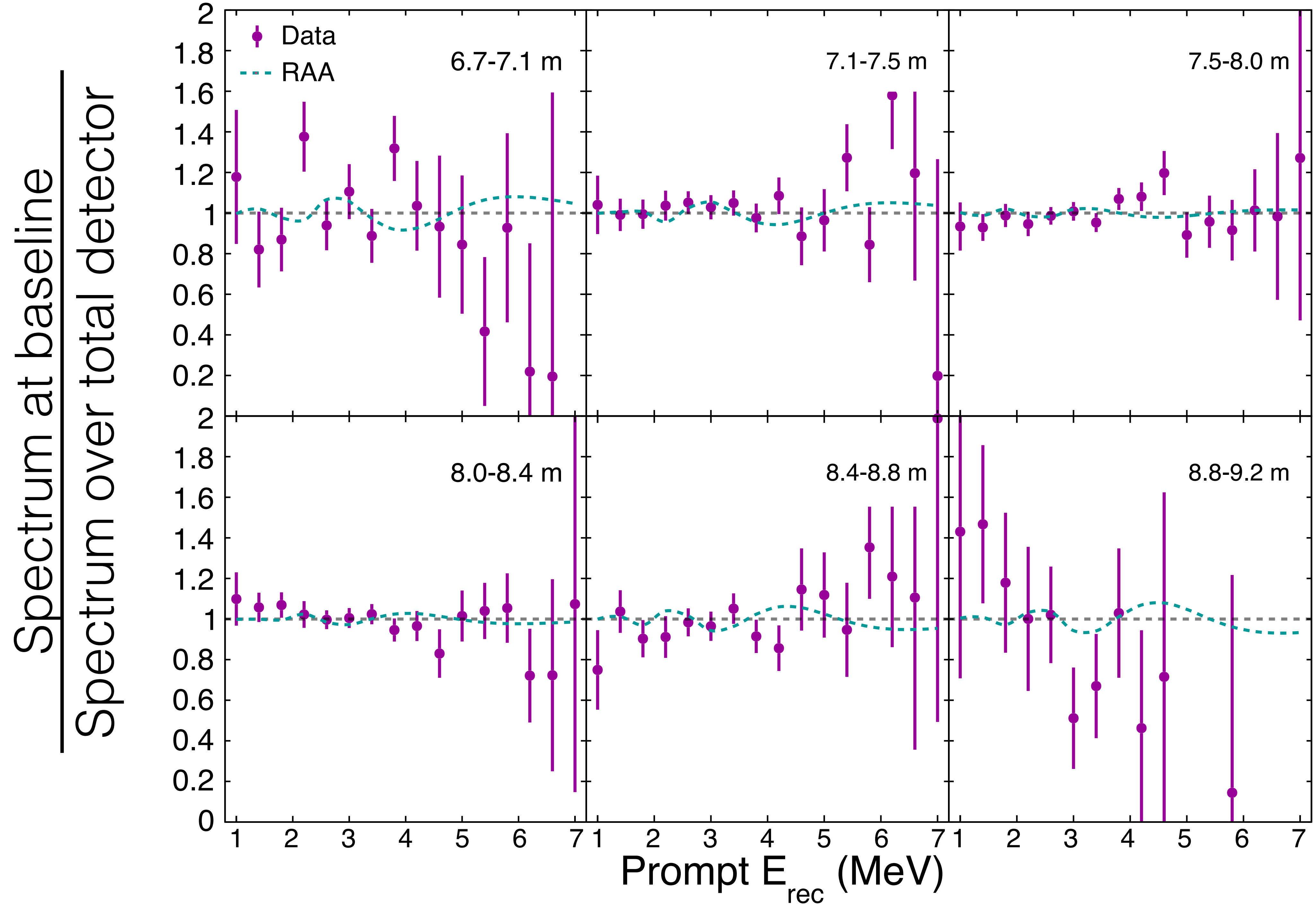
(e) Δz

^{227}Ac Rate vs Baseline (Osc. Set)



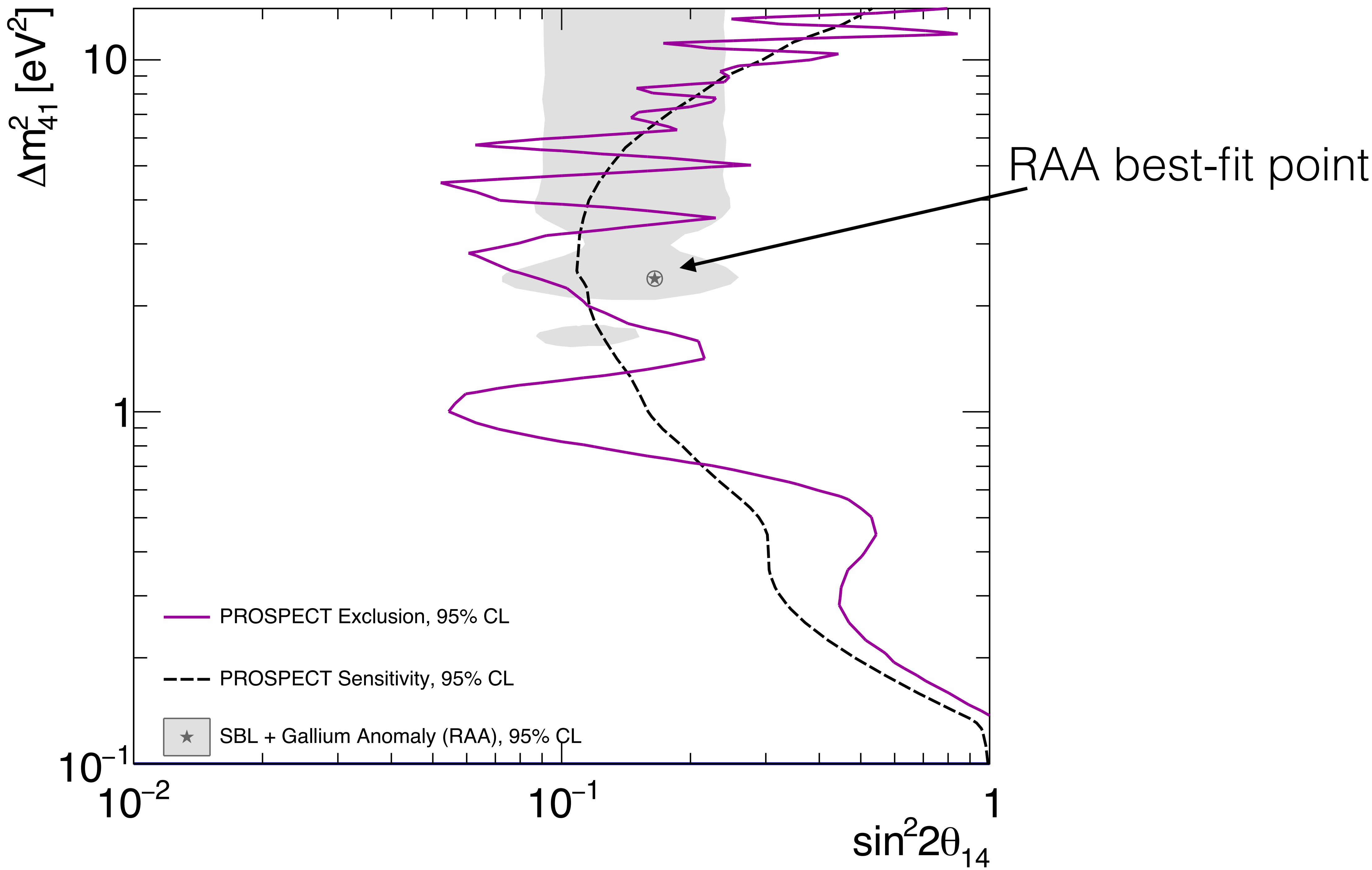


Model Independent Oscillation Search



No significant deviations from no-oscillation prediction

PROSPECT Sensitivity



Disfavor the RAA best-fit point at a 2.2σ confidence level

^{235}U Spectrum

World-leading ^{235}U antineutrino spectrum