Short-Wavelength Reactor Neutrino Oscillations

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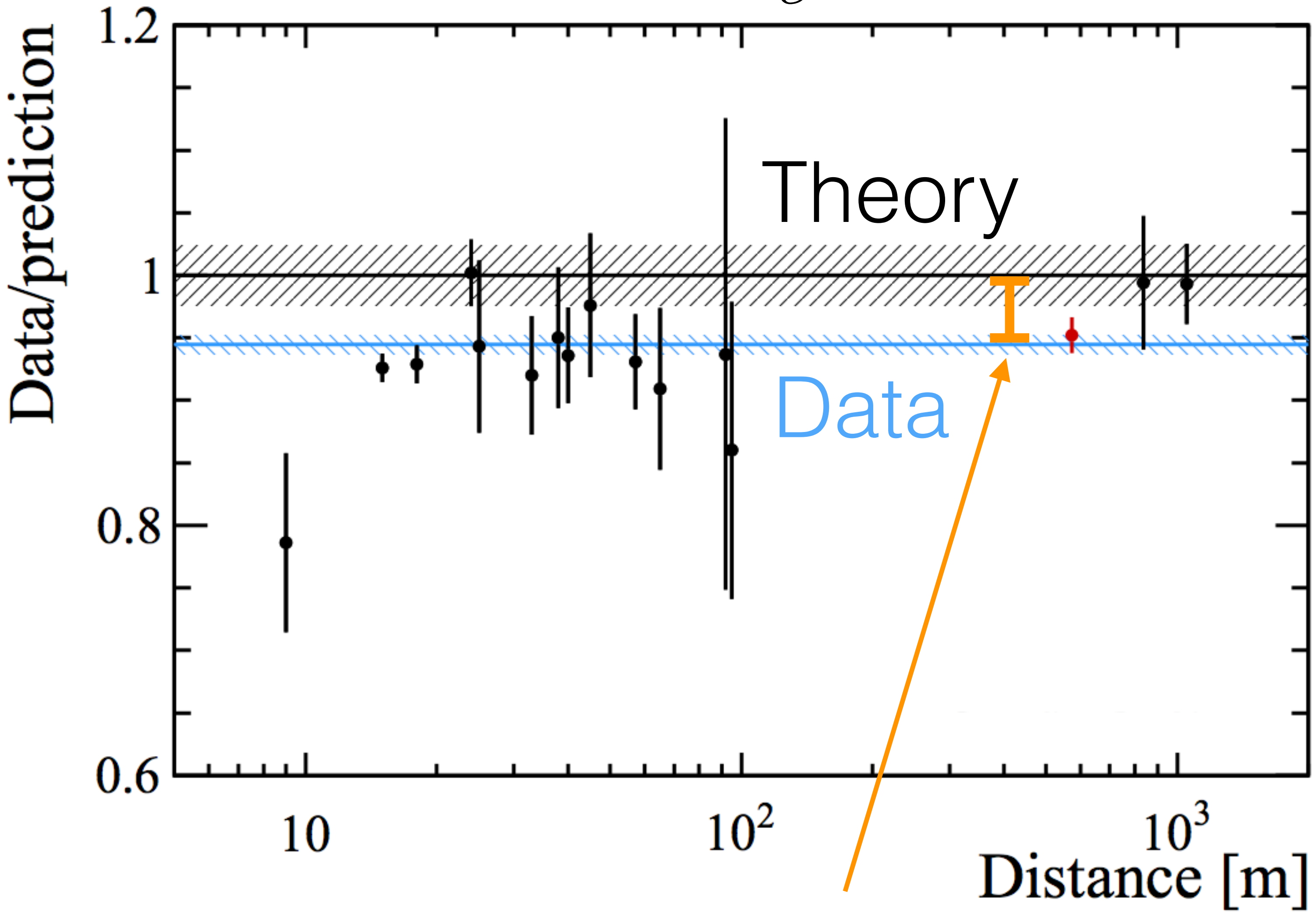
The Reactor Antineutrino Anomaly

Inverse Beta Decay

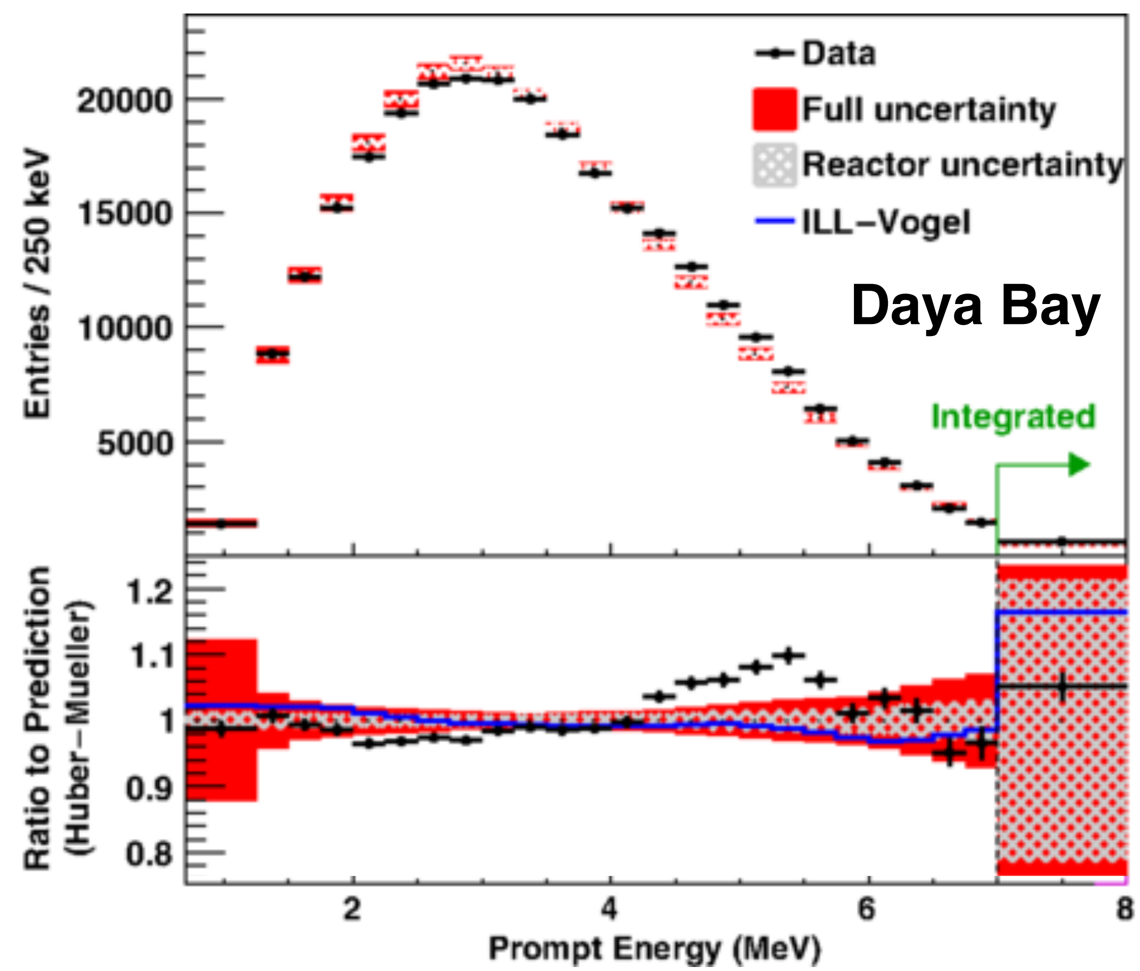
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Reactor $\bar{\nu}_e$ Flux



~6% deficit

Prompt Energy



Hypotheses:

(1) Sterile neutrino

(2) Flux models are incomplete

The PROSPECT Experiment

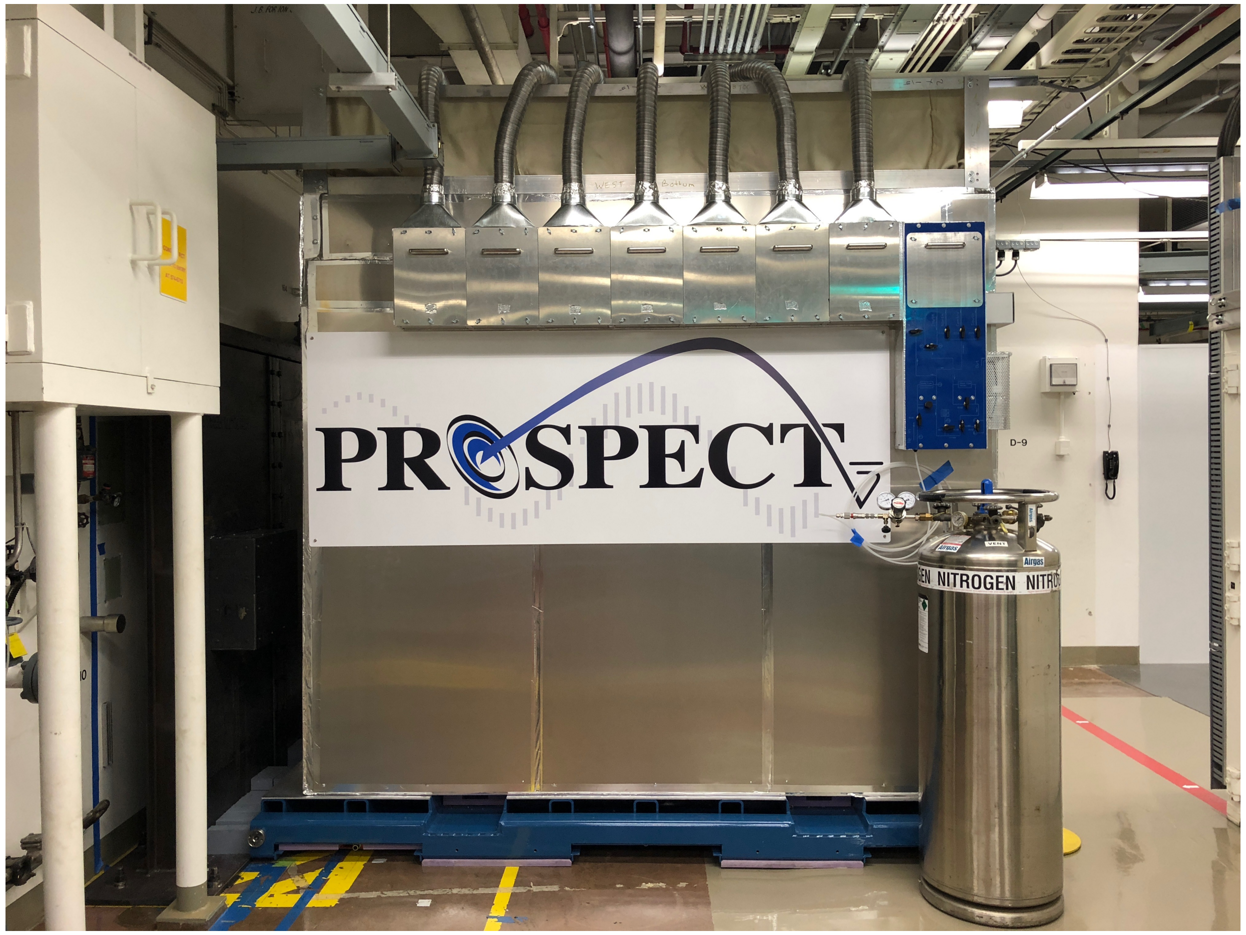
Precision Reactor Oscillation and SPECTrum Experiment

Physics Goals:

(1) Search for eV-scale sterile neutrino oscillations

(2) Measure the ^{235}U antineutrino spectrum

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

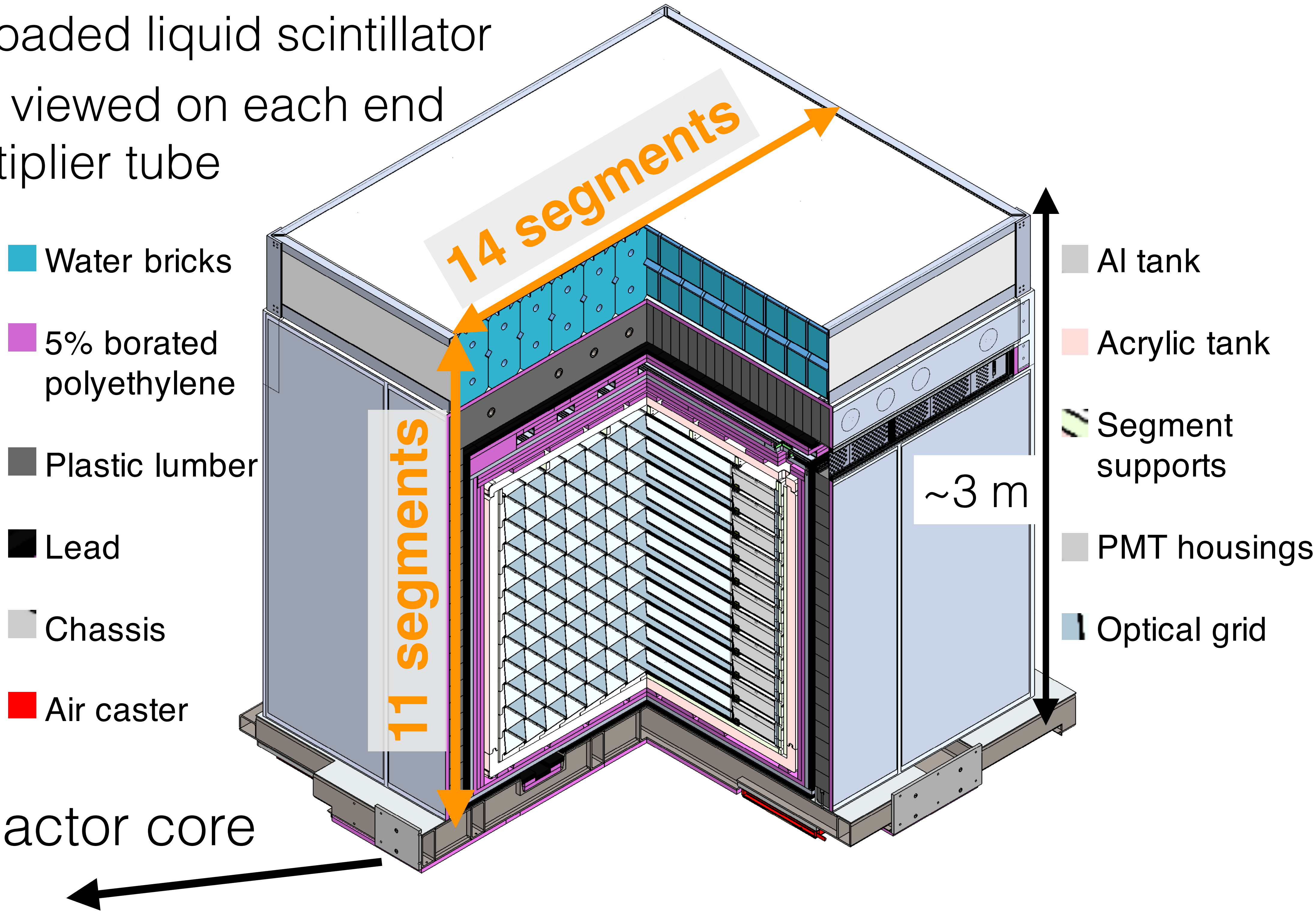


PROSPECT Antineutrino Detector

154 optically separated segments

Filled with ^{6}Li loaded liquid scintillator

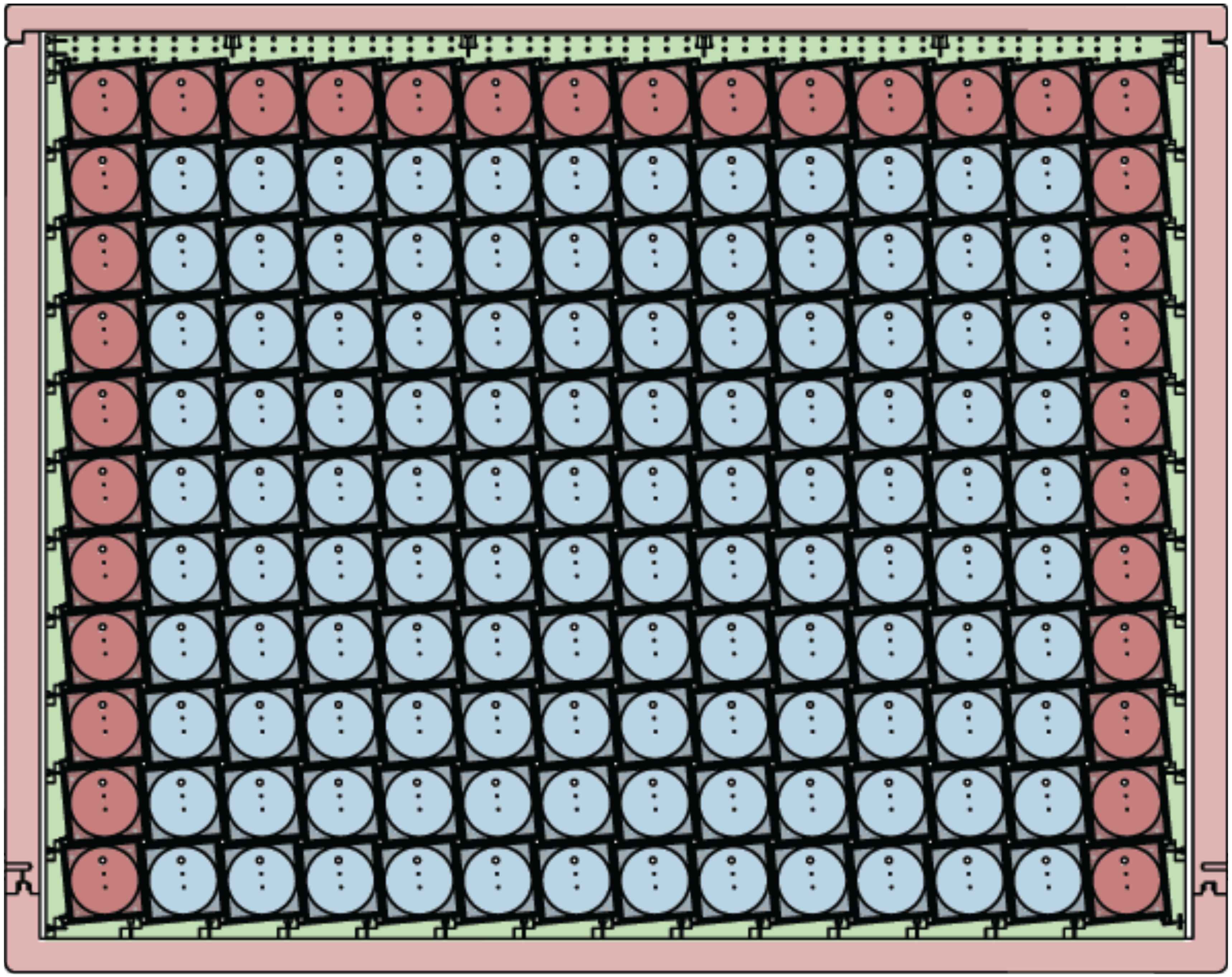
Each segment viewed on each end by a photomultiplier tube



Photomultiplier Tubes (PMT)

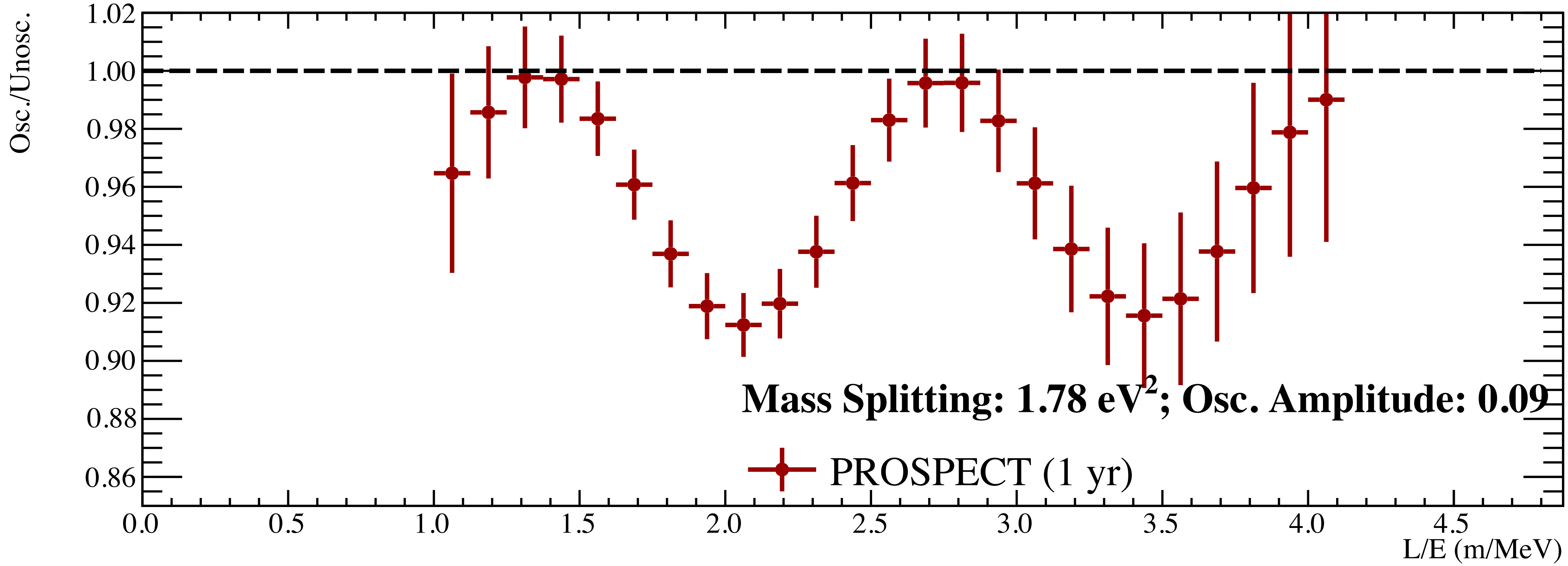
68 ET Tubes - Outer Shell

240 Hamamatsu Tubes - Fiducial Volume



Oscillation Search

After 1 year of data, if PROSPECT detected a sterile neutrino, the measured spectrum would look like this:



Volume variations in the detector could mimic this signal, with *no* sterile neutrino present

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

^{227}Ac as a Calibration Source

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

$t_{1/2}$=3.96 s $\qquad$ $t_{1/2}$=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

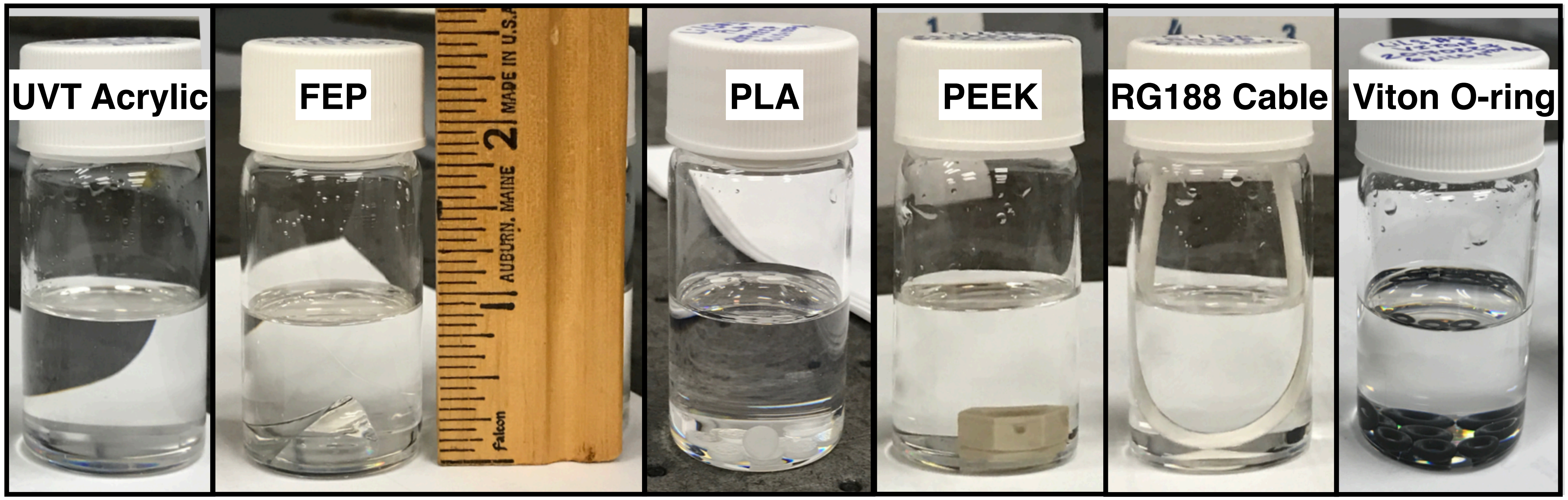
Low background source

Highly localized signal

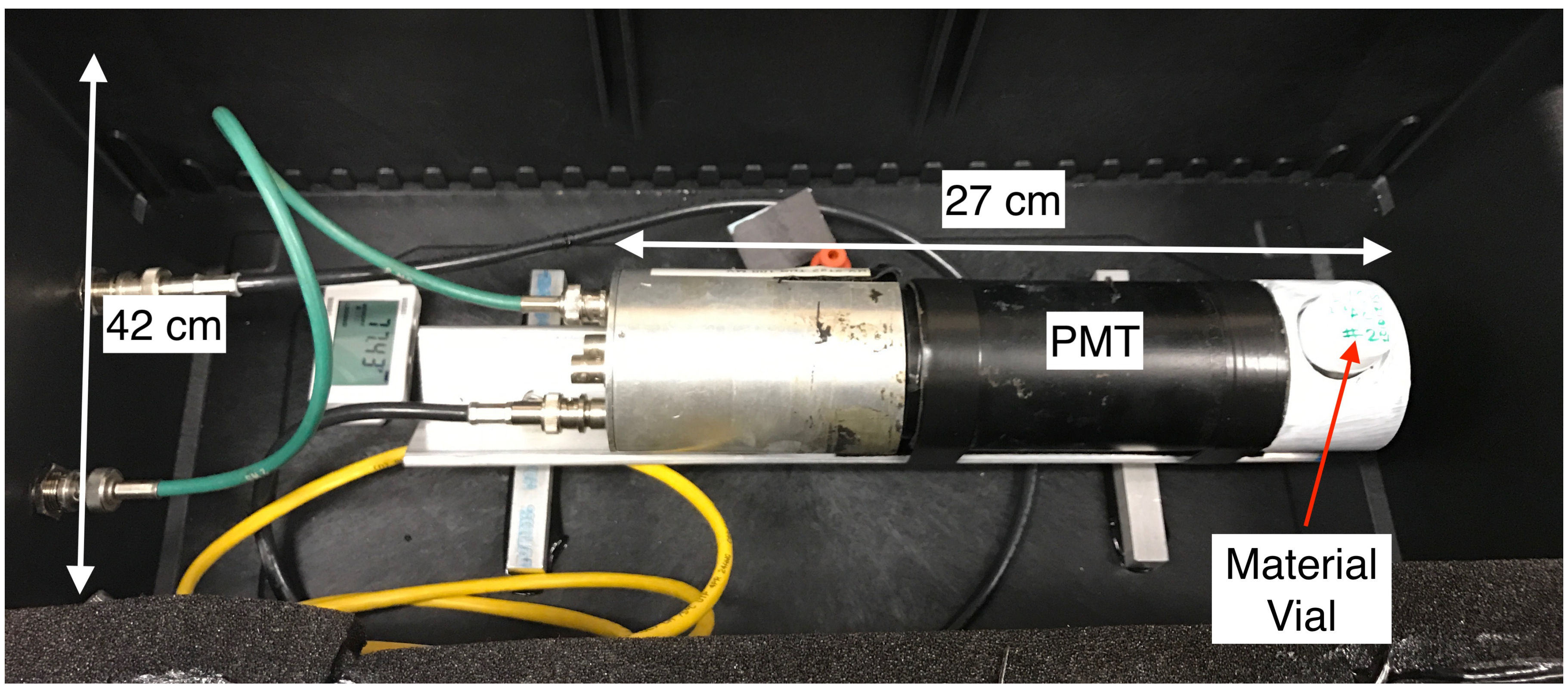
Used to measure segment-to-segment volume variations

Material Compatibility

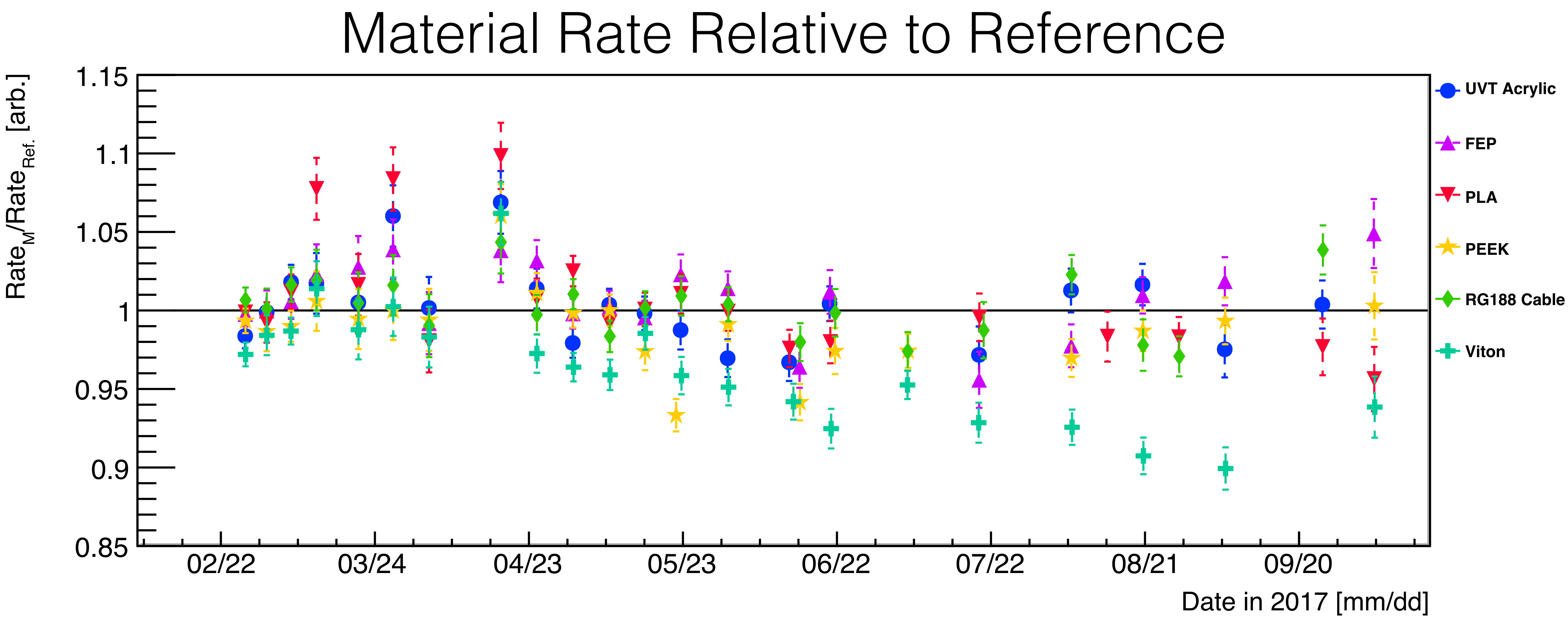
To determine that ^{227}Ac did not adsorb onto detector materials



+ Reference vial (no material)



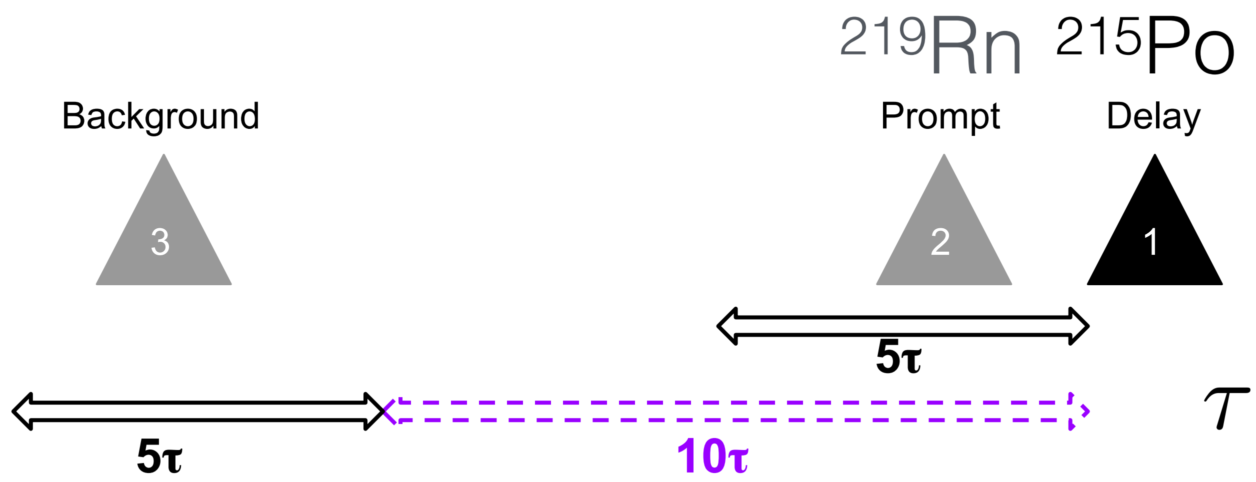
Material Study Results



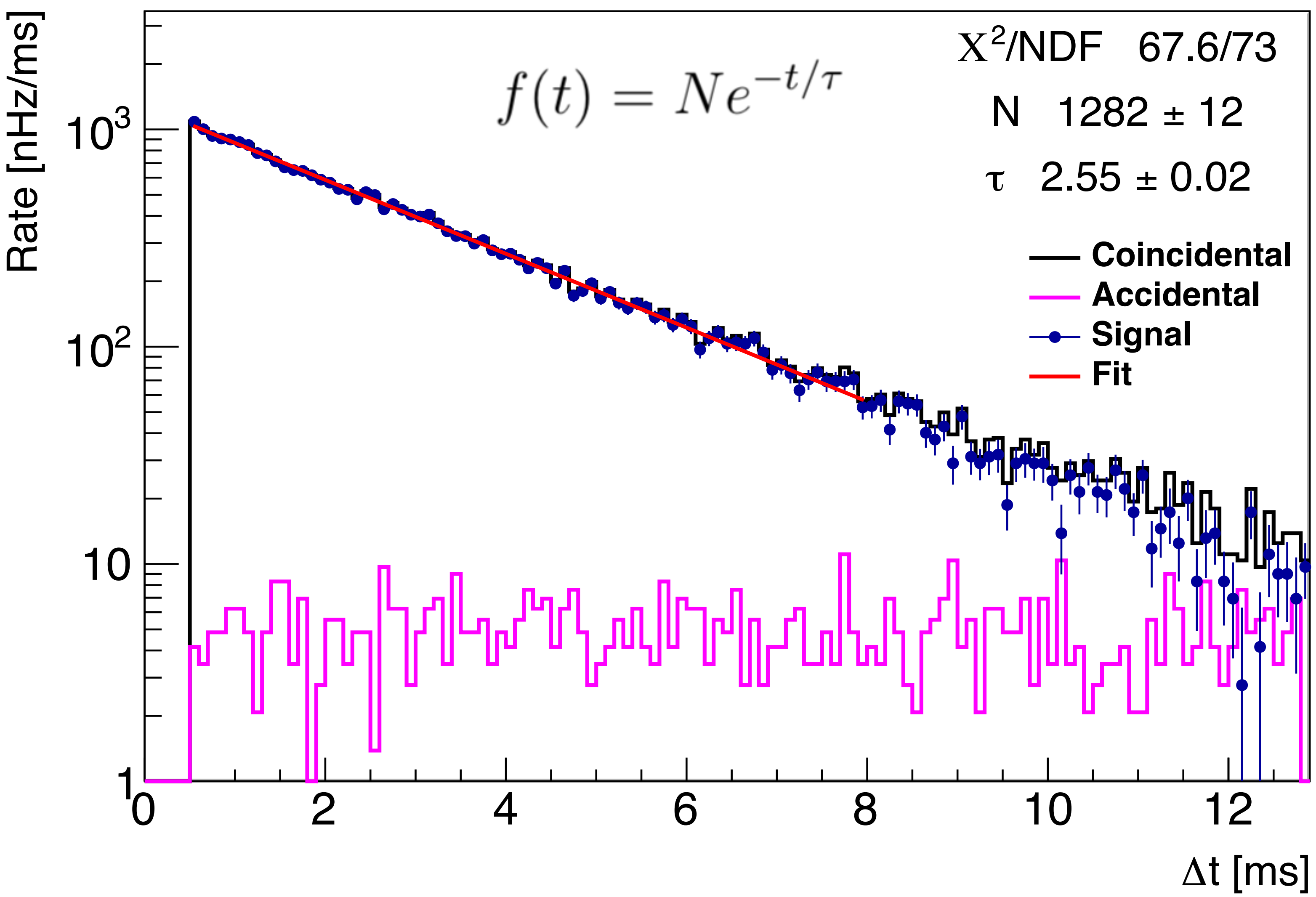
No clear sign of adsorption*

*decrease in viton due to threshold effects, not adsorption

^{227}Ac in the PROSPECT Detector



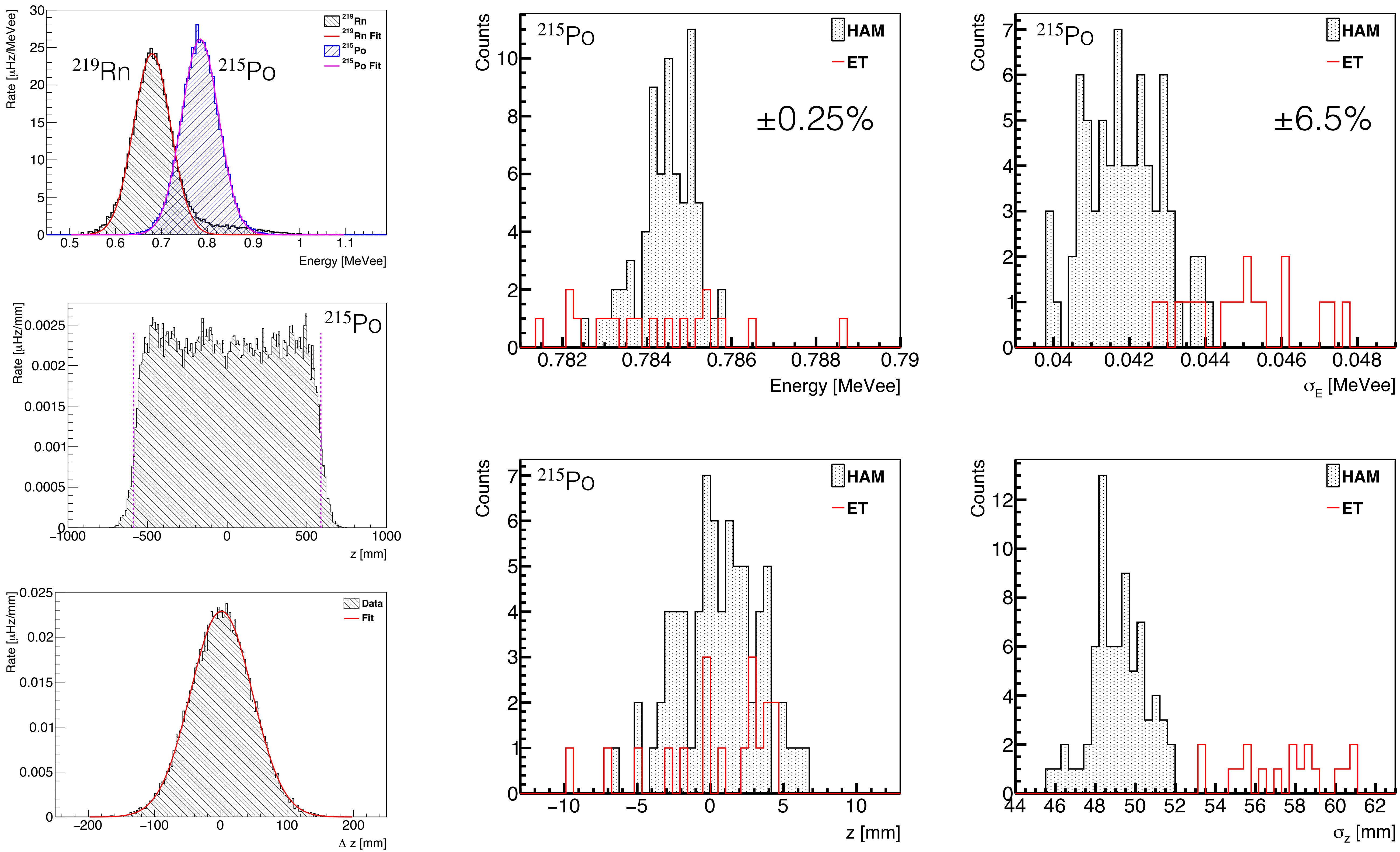
$\tau = 2.57$ ms



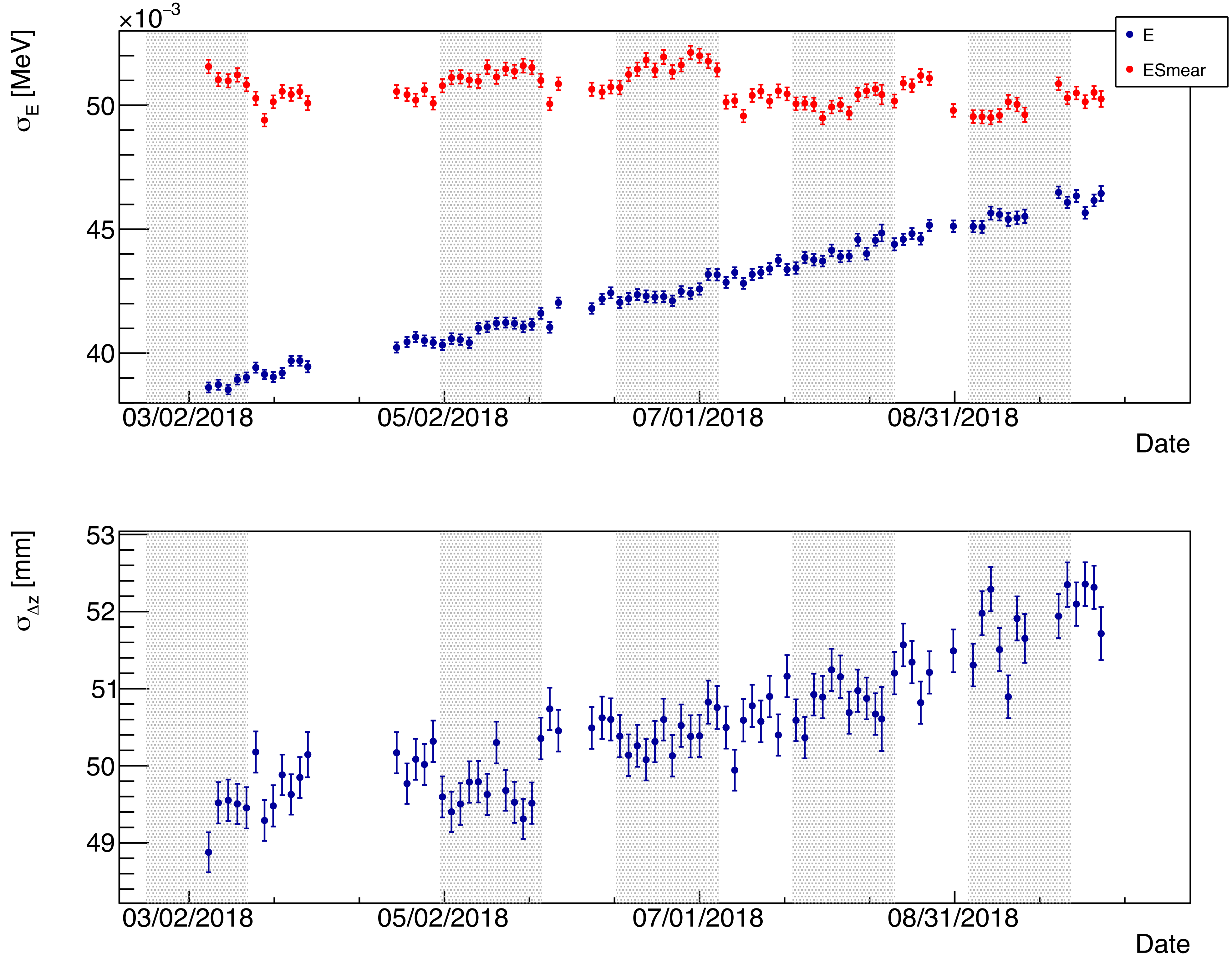
$$R = \frac{N\ \tau}{\Delta t\text{-bin-width} \times \text{livetime} \times \text{efficiency}}$$

Efficiency > 99.9%
Livetime = 4011.7 hrs

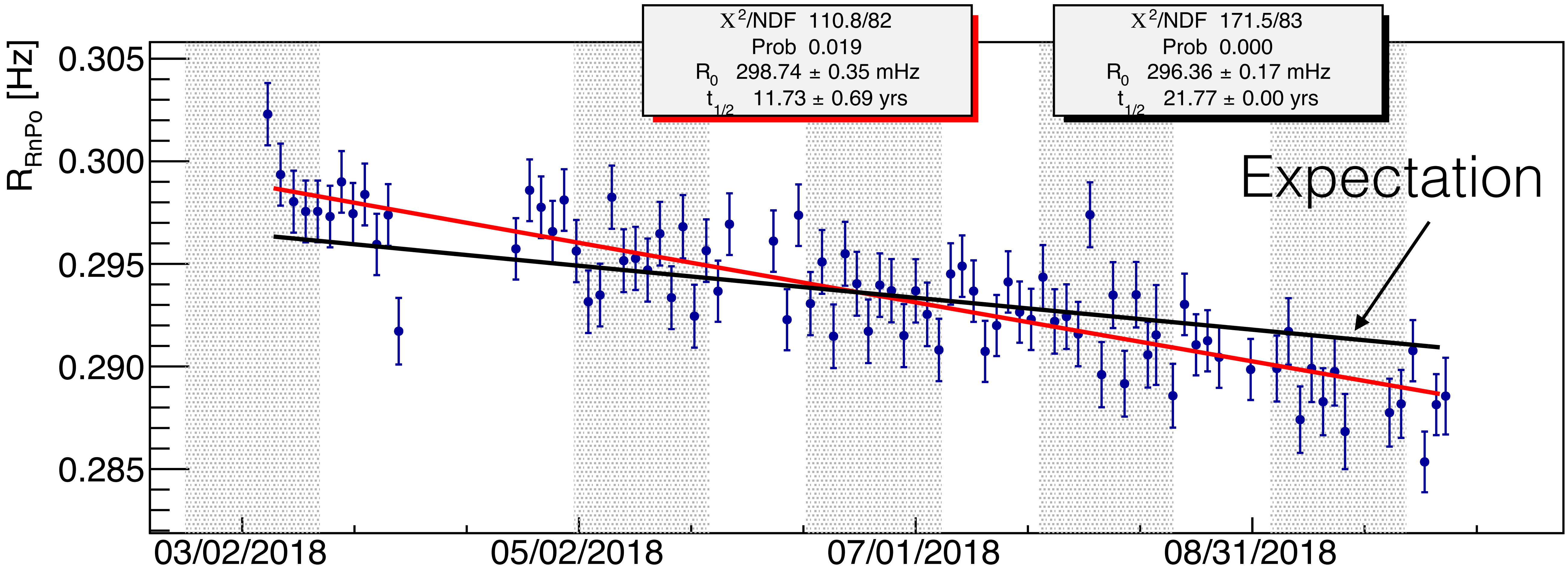
Segment-to-Segment Stability



Position and Energy Resolution of Alphas



^{227}Ac Rate Versus Time

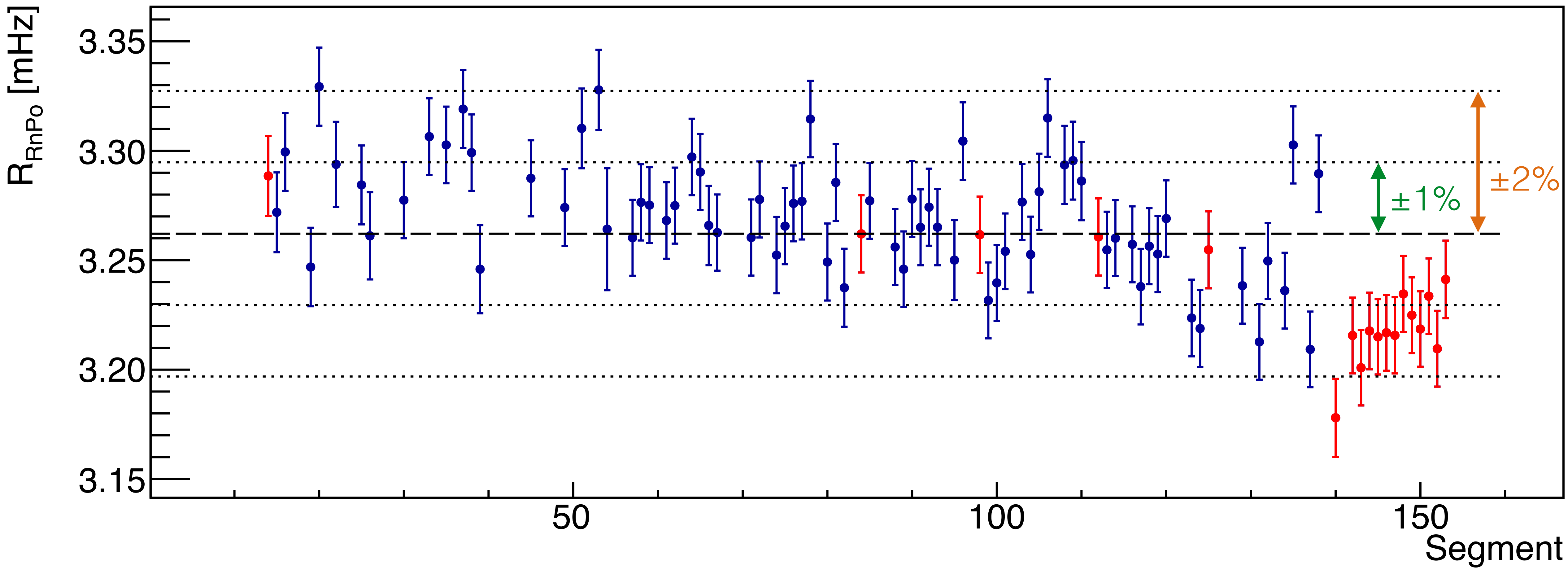


Decaying 1.56 ± 0.21% faster than expectation

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

^{227}Ac Rate Per Segment

Average = 3.262 ± 0.002 mHz



standard deviation of HAM segments = 0.026 mHz

Systematic Errors

±1%: 227Ac decay rate falling faster than expectation

±0.15%: energy, PSD, and dz cuts

±0.22%: contamination from other alpha coincidence sources

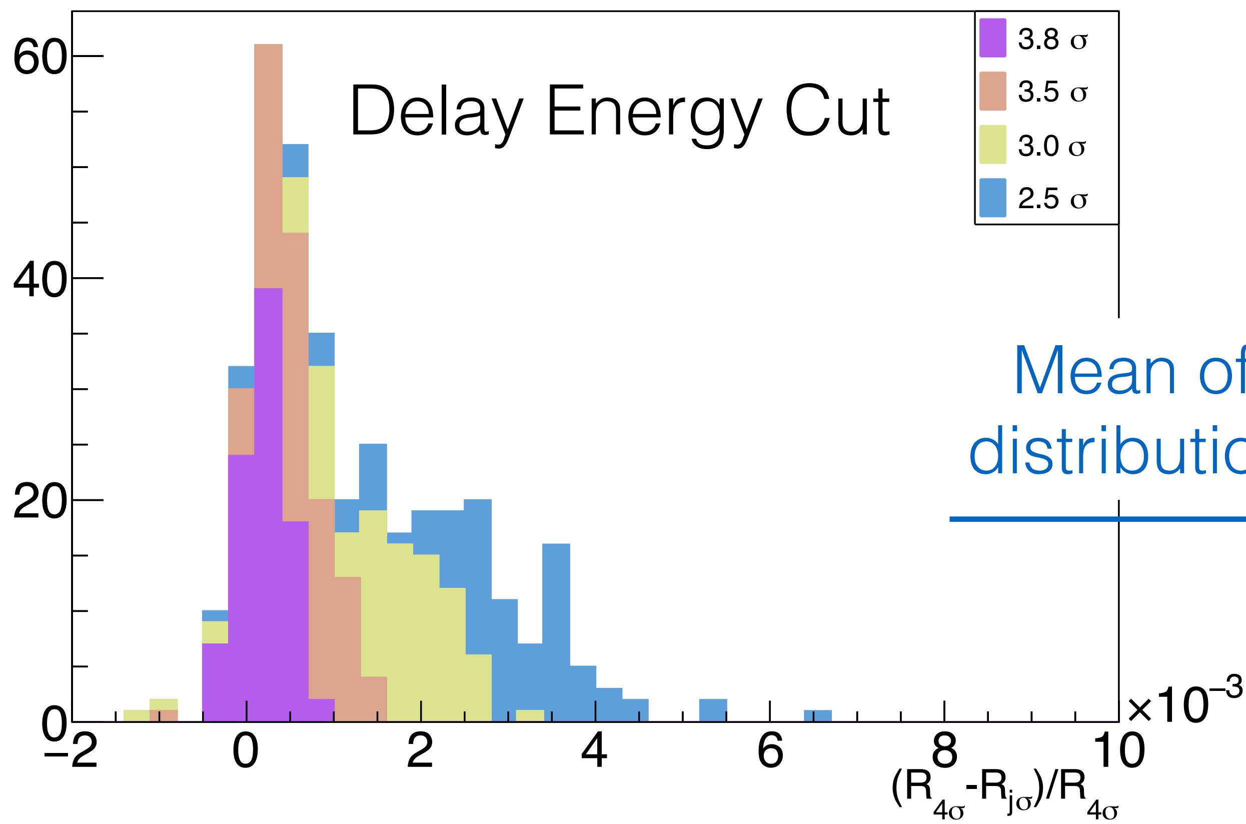
Systematic Error: Cuts

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

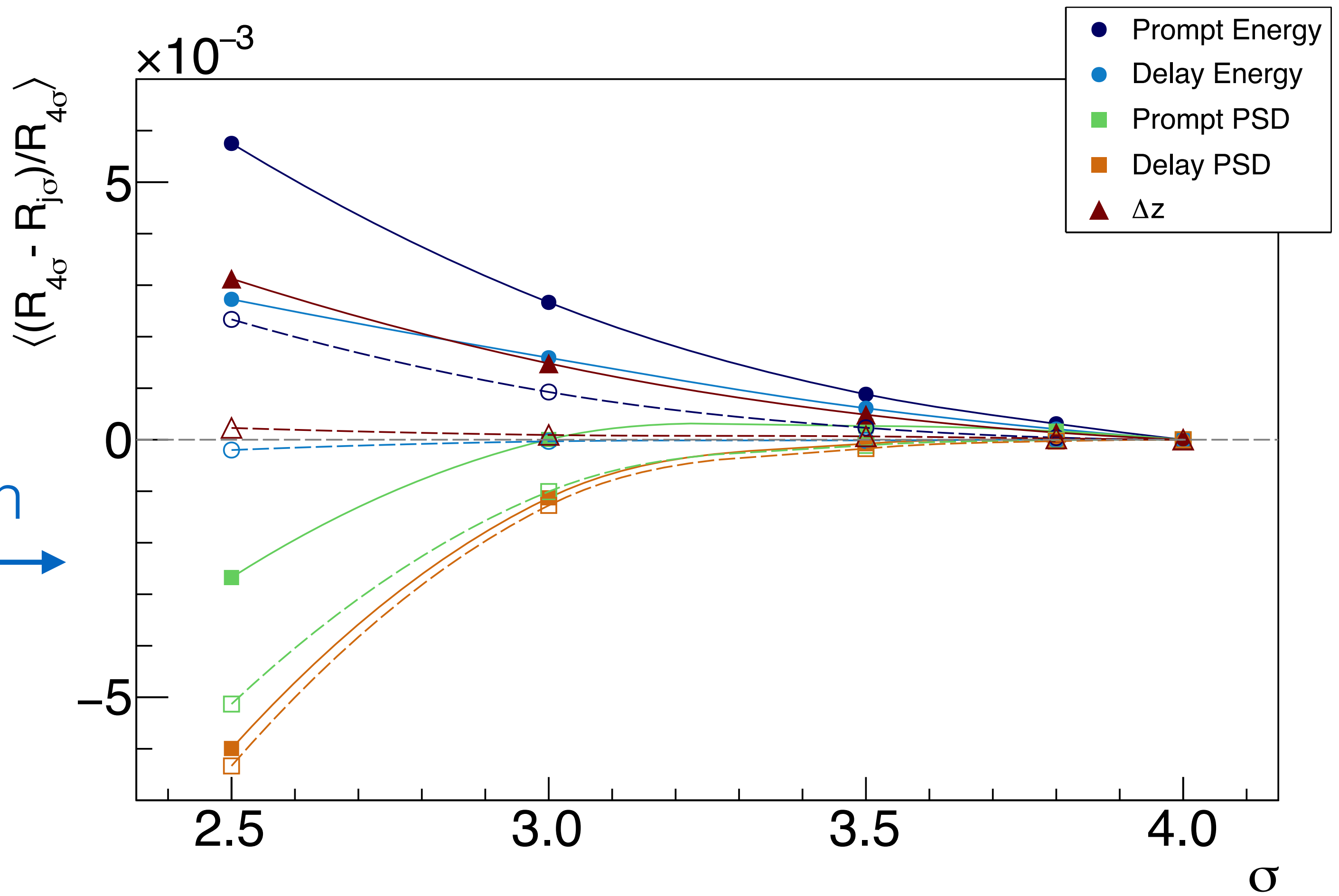
For each segment calculate:

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

Distribution



Mean of distribution



Systematic Error: Other Alphas

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

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

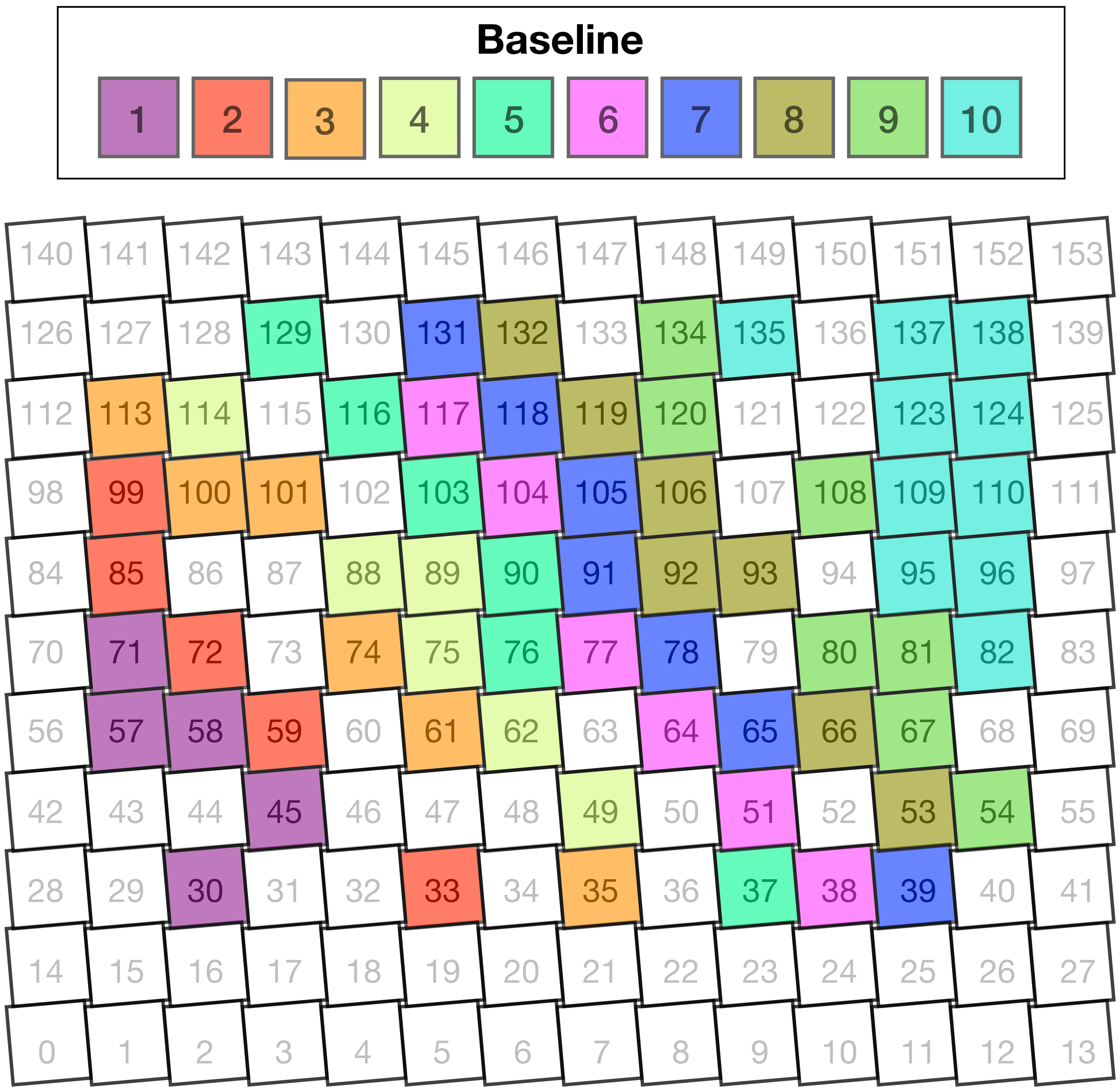
^{219}Rn (^{215}Po) Energy Range is 0.48 (0.61) - 1.18 MeVee

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%

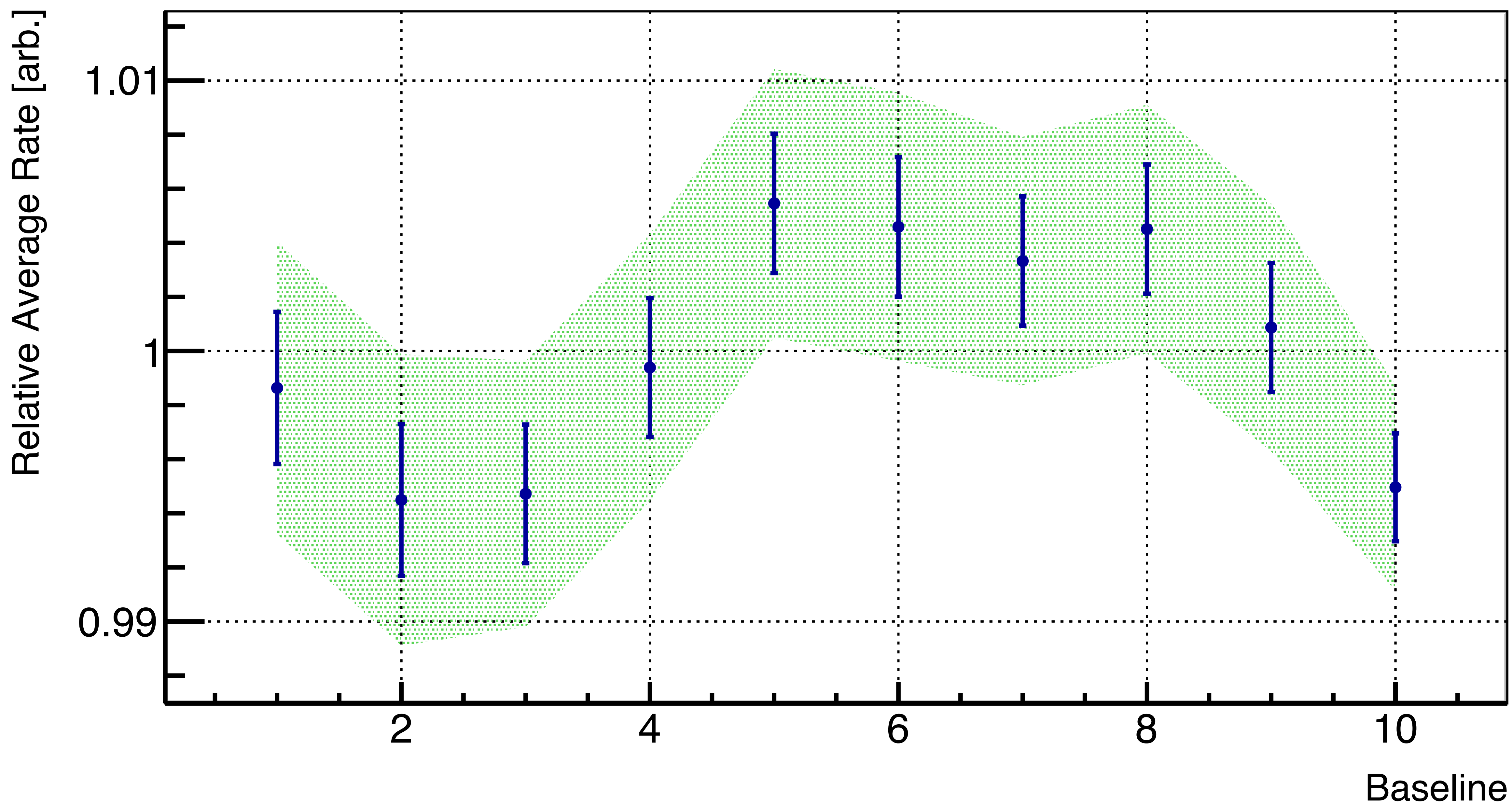
*Assuming an 227Ac rate of 240 mHz

^{227}Ac Rates to Volume Variations



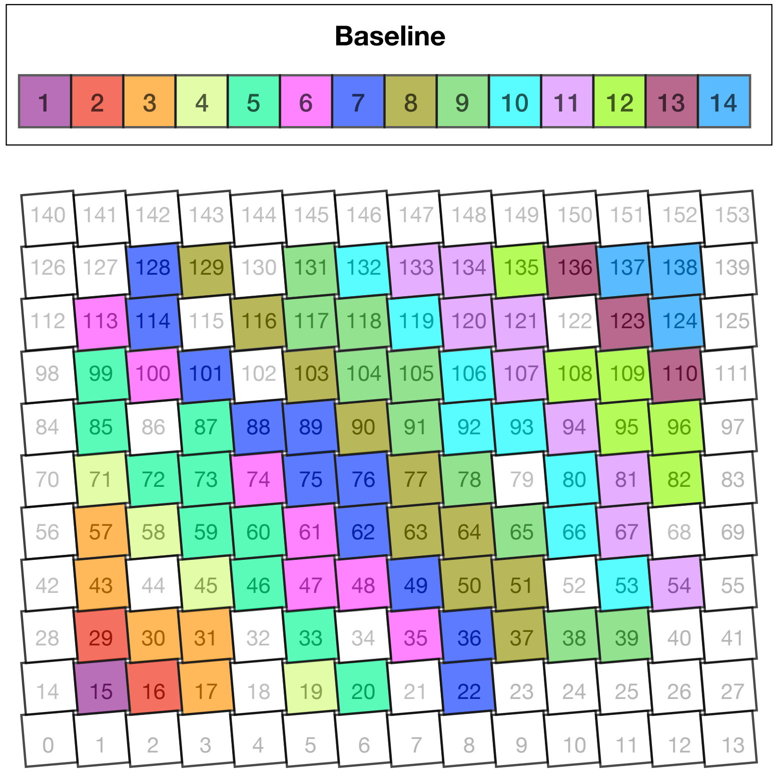
Calculate average rate per baseline to determine volume variations

^{227}Ac Rate Per Baseline



< 1% volume variation over baselines

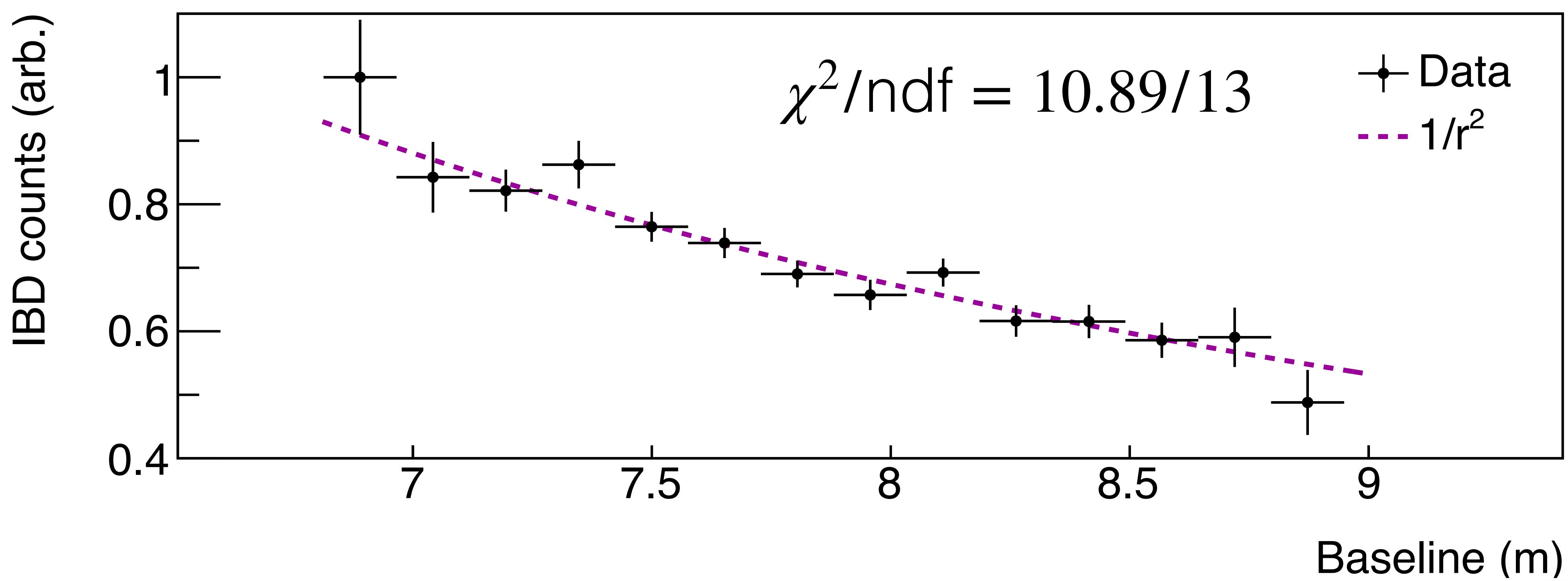
^{227}Ac Rate Per Baseline



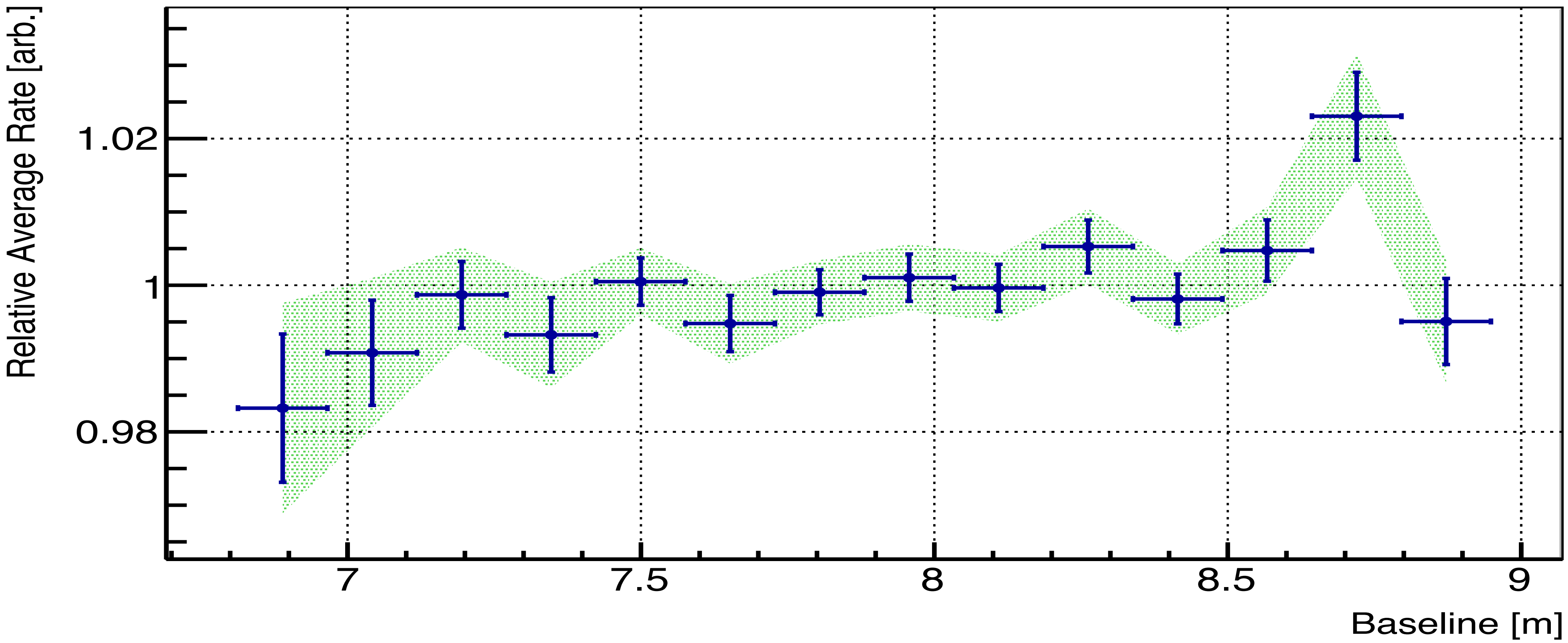
Same procedure for published data set.

Apply corrections to IBD rate versus baseline

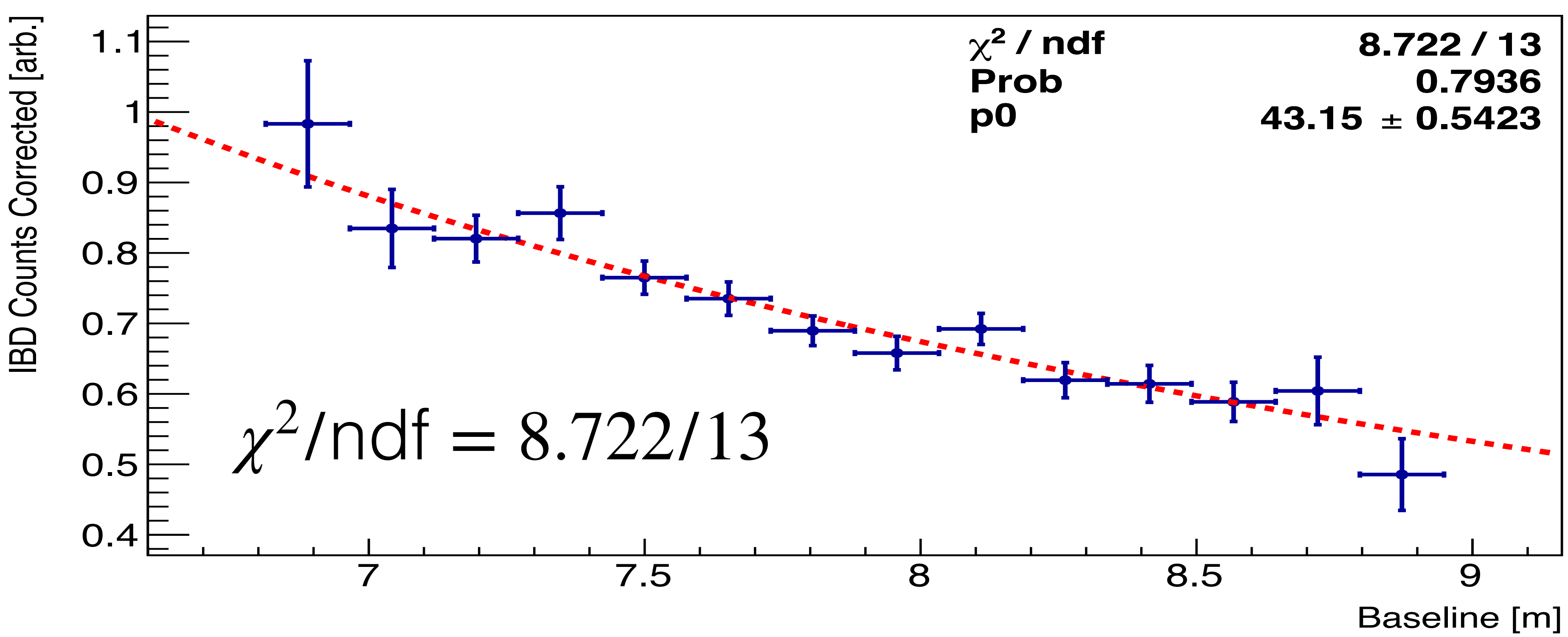
J. Ashenfelter et al. First Search for Short-Baseline Neutrino Oscillations at HFIR with PROSPECT. *Phys. Rev. Lett.*, 121:251802, Dec 2018.



^{227}Ac Rate Per Baseline

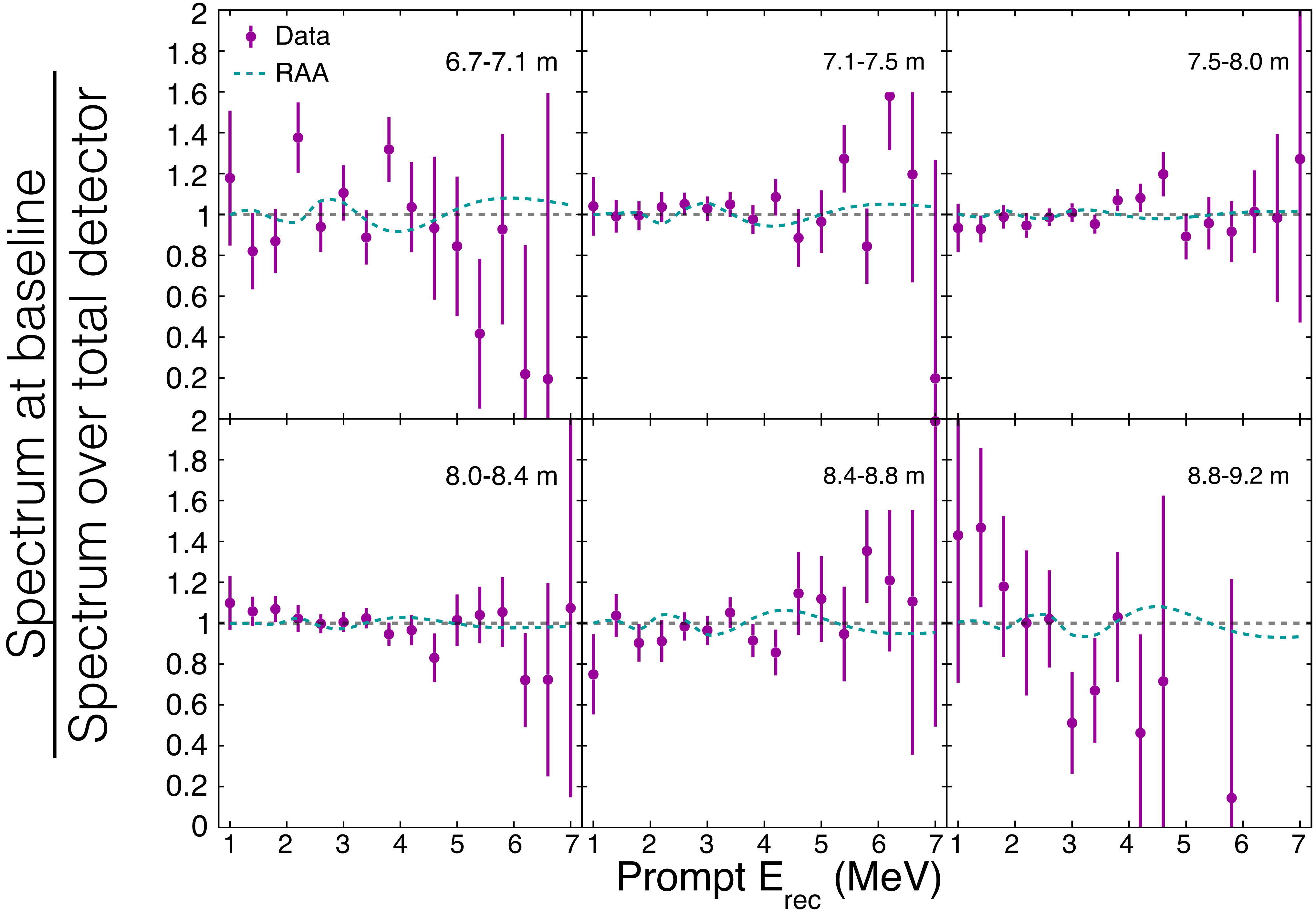


~2% volume variation over baselines.
5% error was included in oscillation analysis.



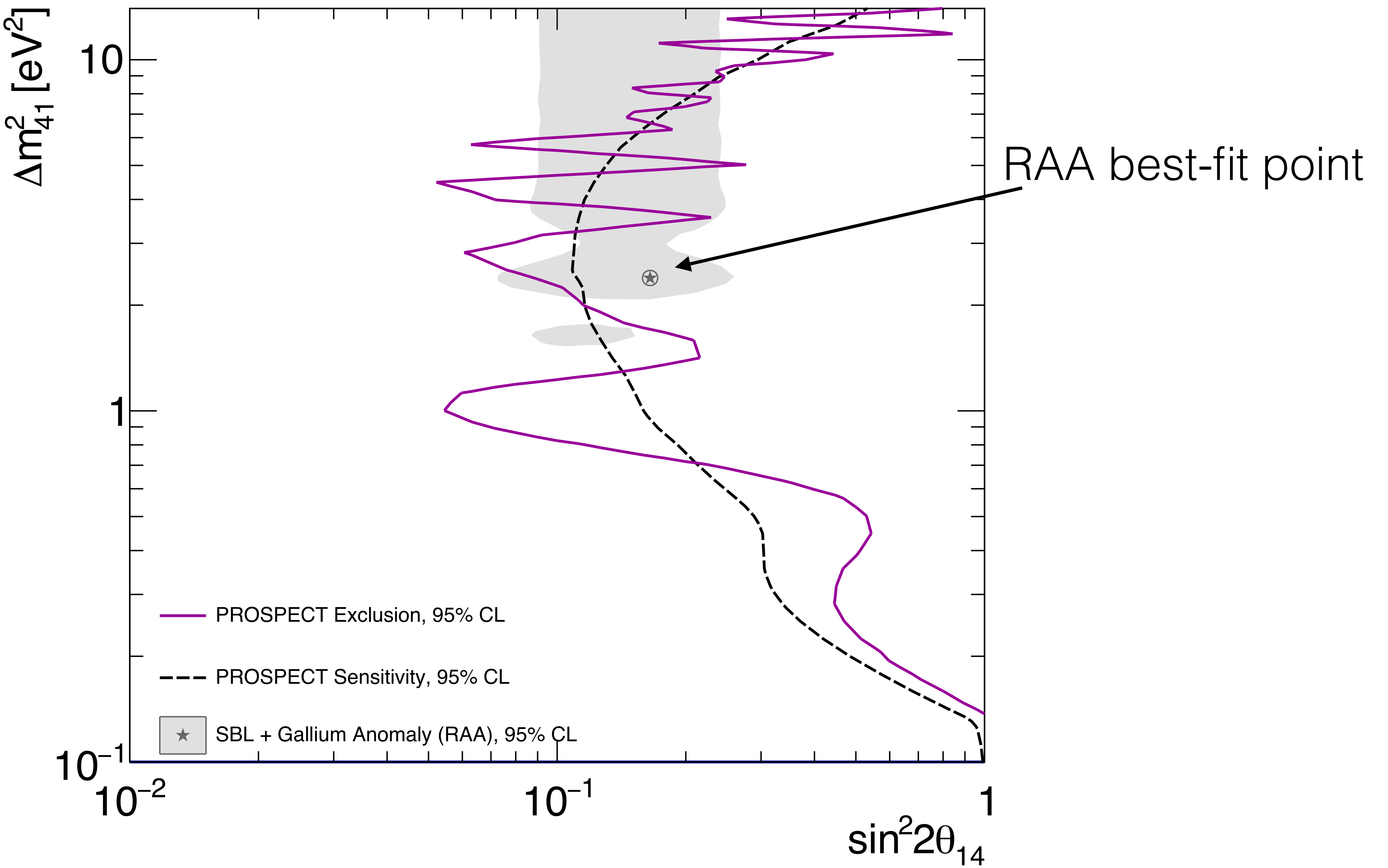
Better chi-squared!

Model Independent Oscillation Search



No significant deviations from no-oscillation prediction

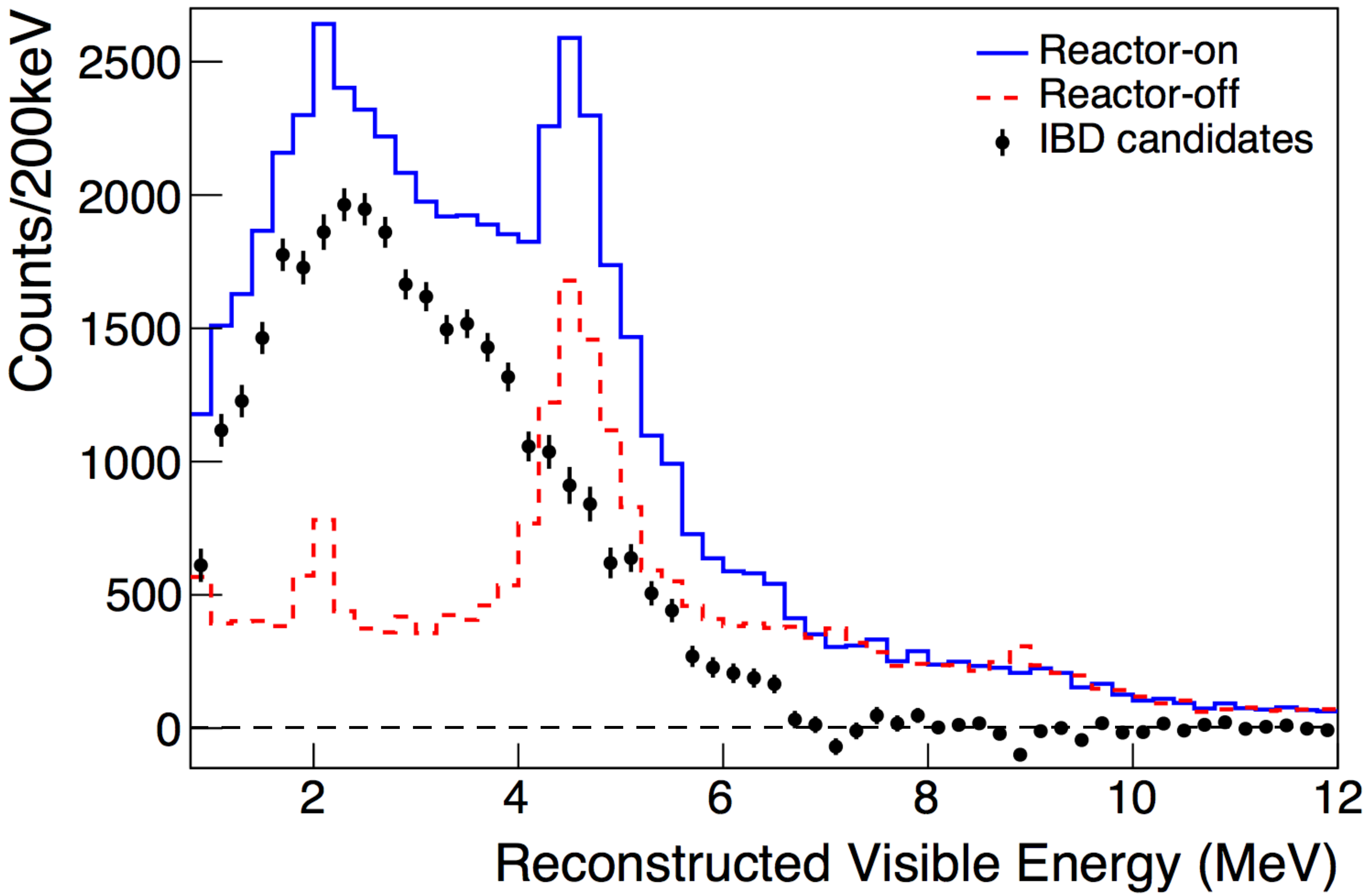
PROSPECT Sensitivity



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

^{235}U Spectrum

World-leading ^{235}U antineutrino spectrum



J. Ashenfelter et al. Measurement of the Antineutrino Spectrum from ^{235}U Fission at HFIR with PROSPECT. *Phys. Rev. Lett.*, 122(25):251801, 2019.

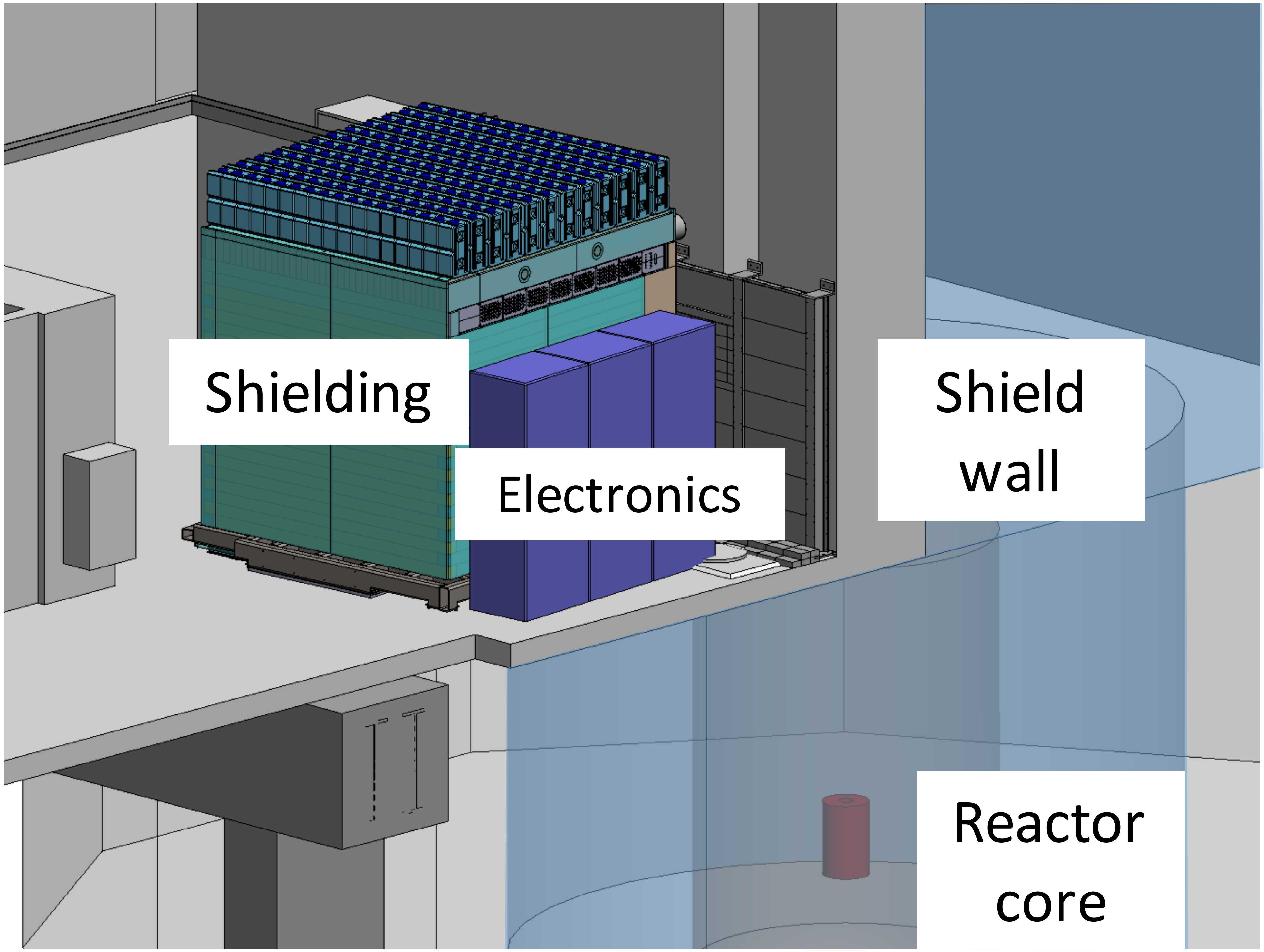
Conclusion

- 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

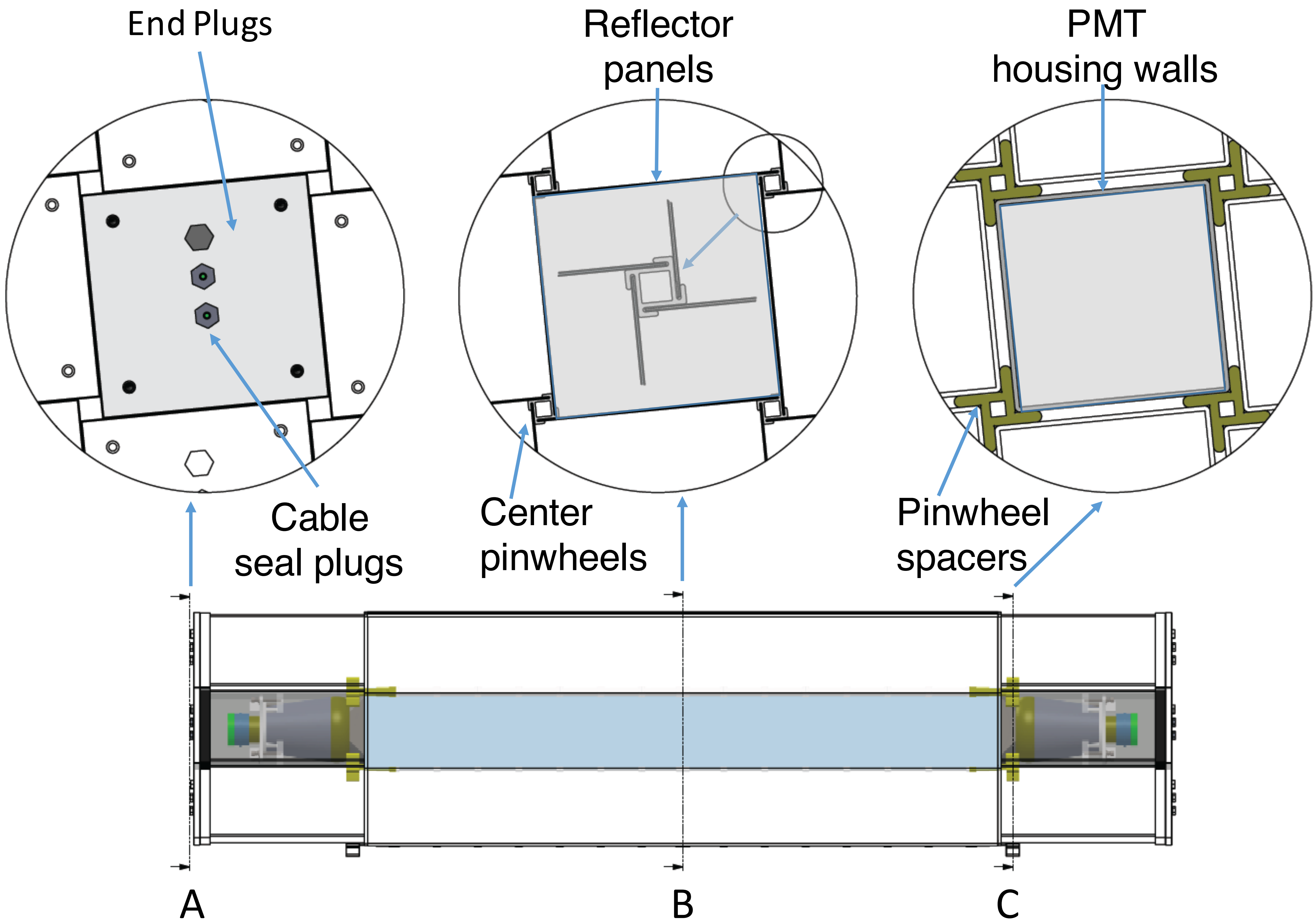
Acknowledgments and Thanks

Backup

PROSPECT



PROSPECT Segment

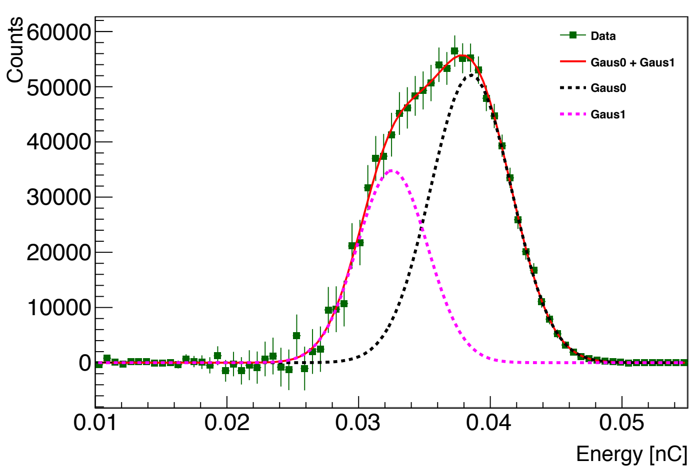


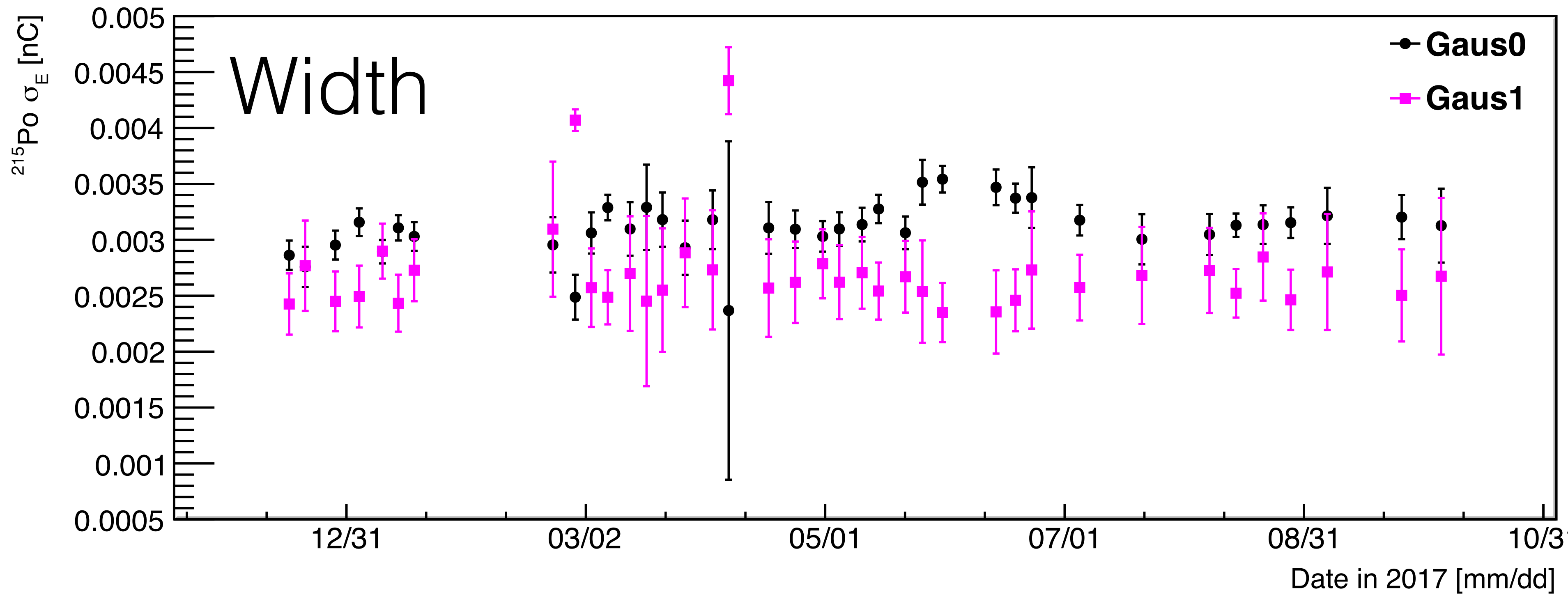
Material Studies

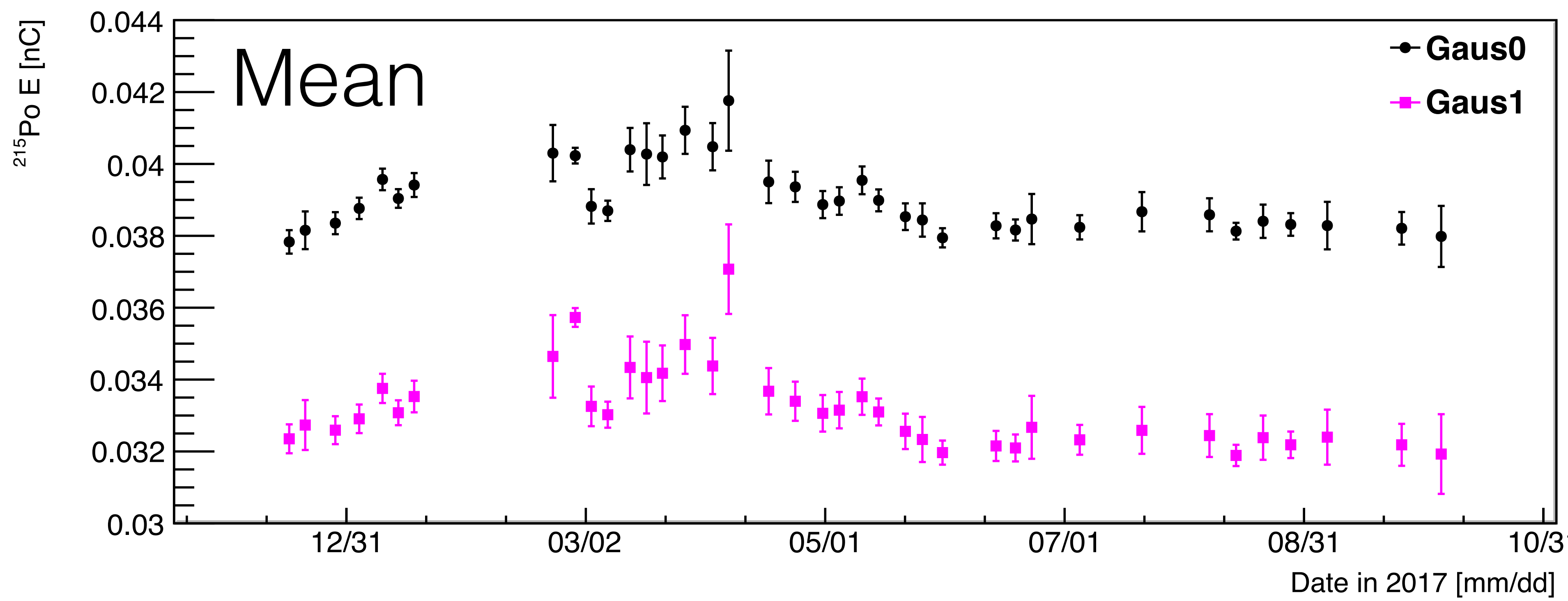
Material	Detector Use	Sample Size
UVT Acrylic	Front window of PMT housing	$1.0 \times 1.15 \times 0.1$ cm^3
FEP	Film on optical separators	1.5×1.5 cm^2, 3 mm thick
PLA	3D printed pinwheels	10 disks; 0.5 cm diameter, 0.1 cm thick
PEEK	Seal plugs through which the high voltage and signal cables were threaded. 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.

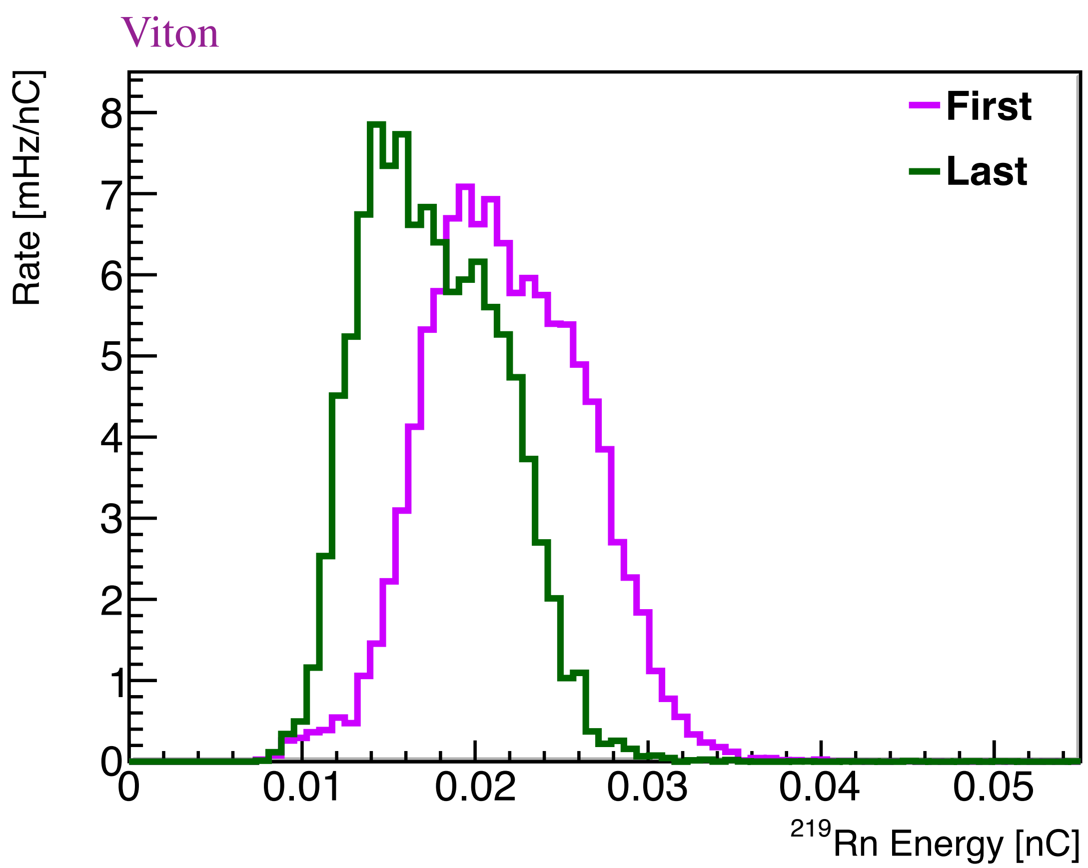
Material Studies - ^{215}Po Energy

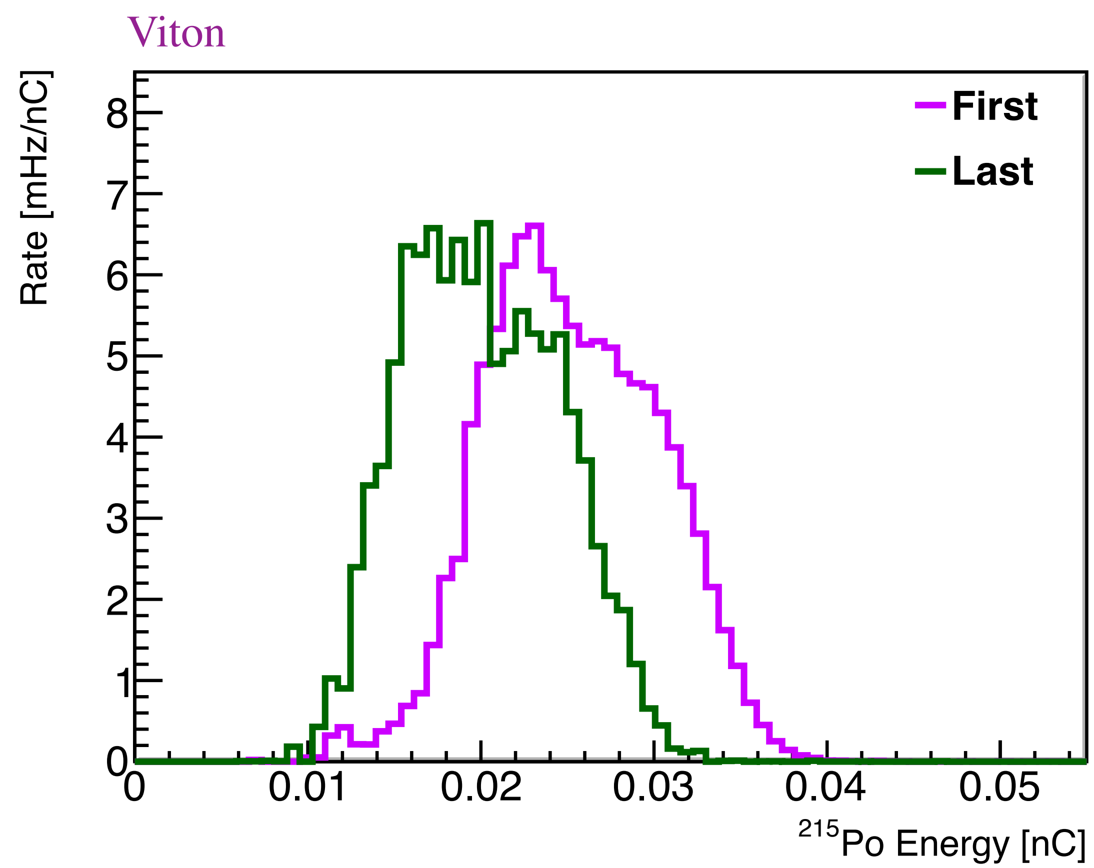


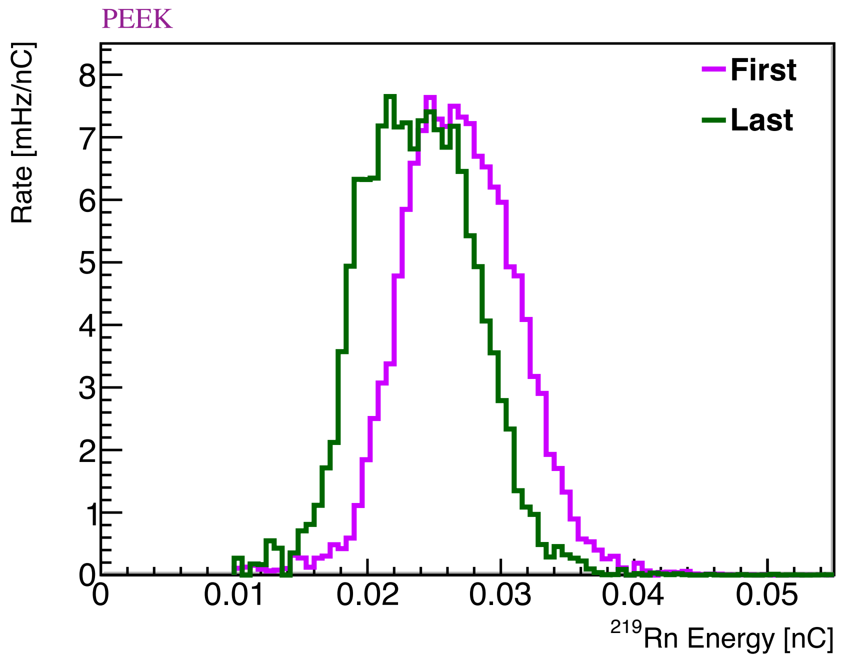


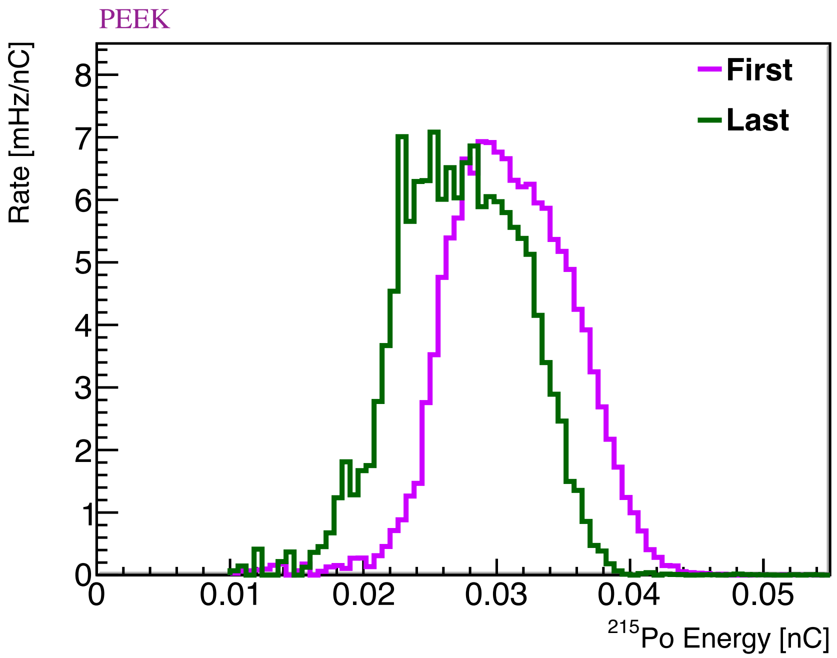


Material Studies - Viton

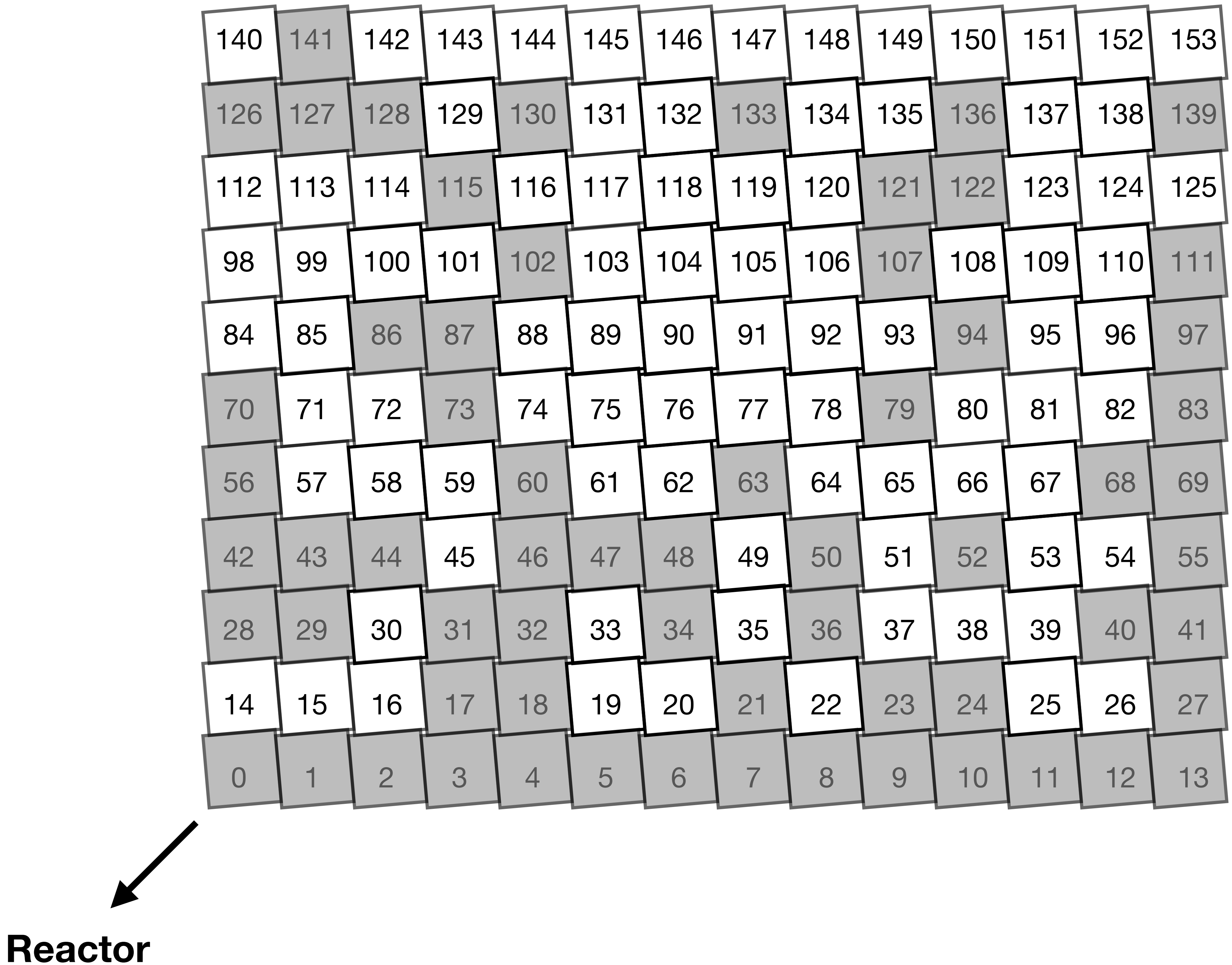






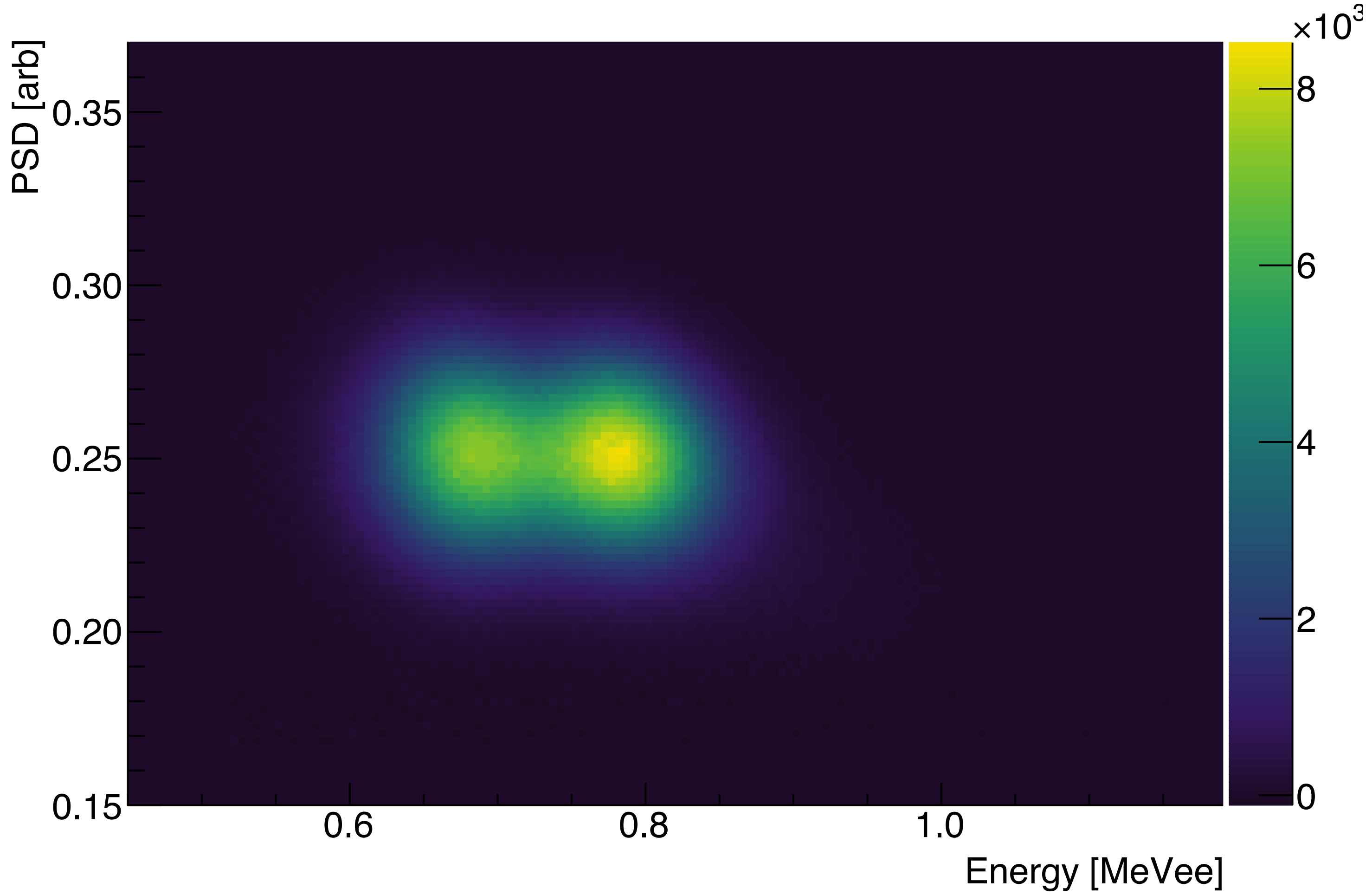


Excluded Segments

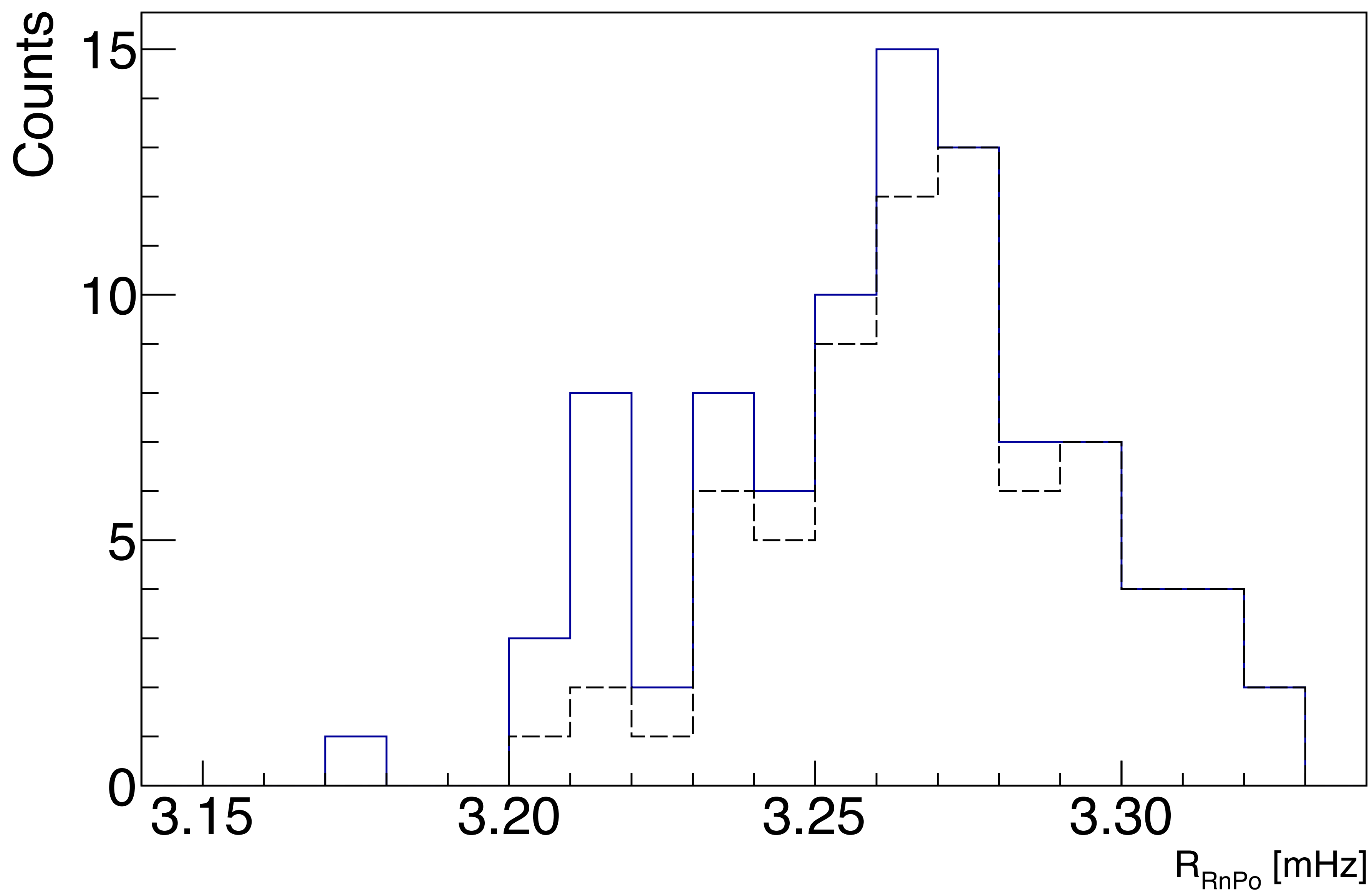


^{227}Ac Broad Cuts

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



Rate Per Segment



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