# A Novel Algorithm for Alpha Discrimination in PICO Bubble Chambers

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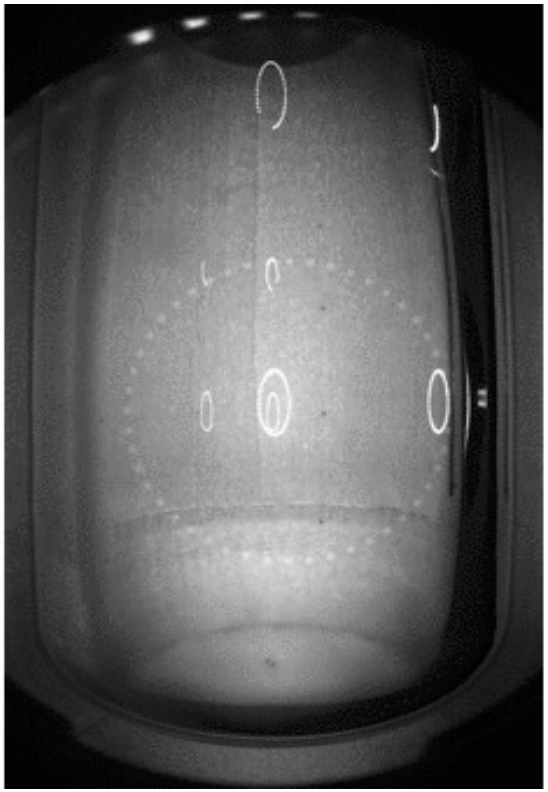
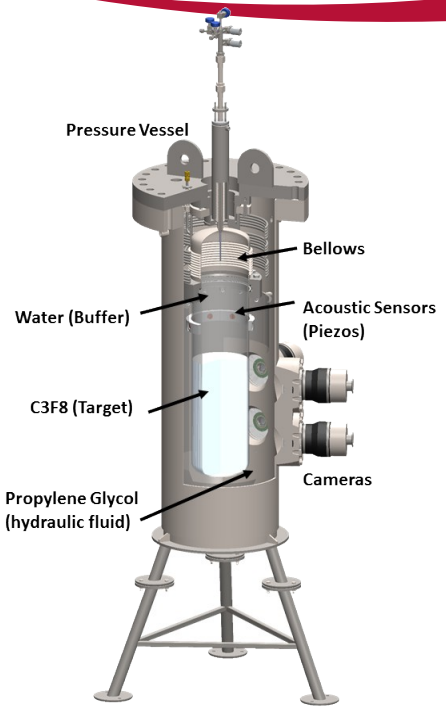
## PICASSO-COUPP (PICO)

- Union of **P**roject **I**n **CA**nada to **S**earch for **S**upersymmetric **O**bjects (PICASSO) and **C**hicagoland **O**bservatory for **U**nderground **P**article **P**hysics (COUPP).
- Operate bubble chamber experiments (primarily at SNOLAB) filled with superheated $C_3F_8$ to search for weakly interacting dark matter (WIMPs).
- PICO bubble chambers excel particularly in alpha discrimination using high-frequency acoustic analysis.

PICASSO-COUPP (PICO)

*(Below) Single bubble event from PICO-60 exposure.*

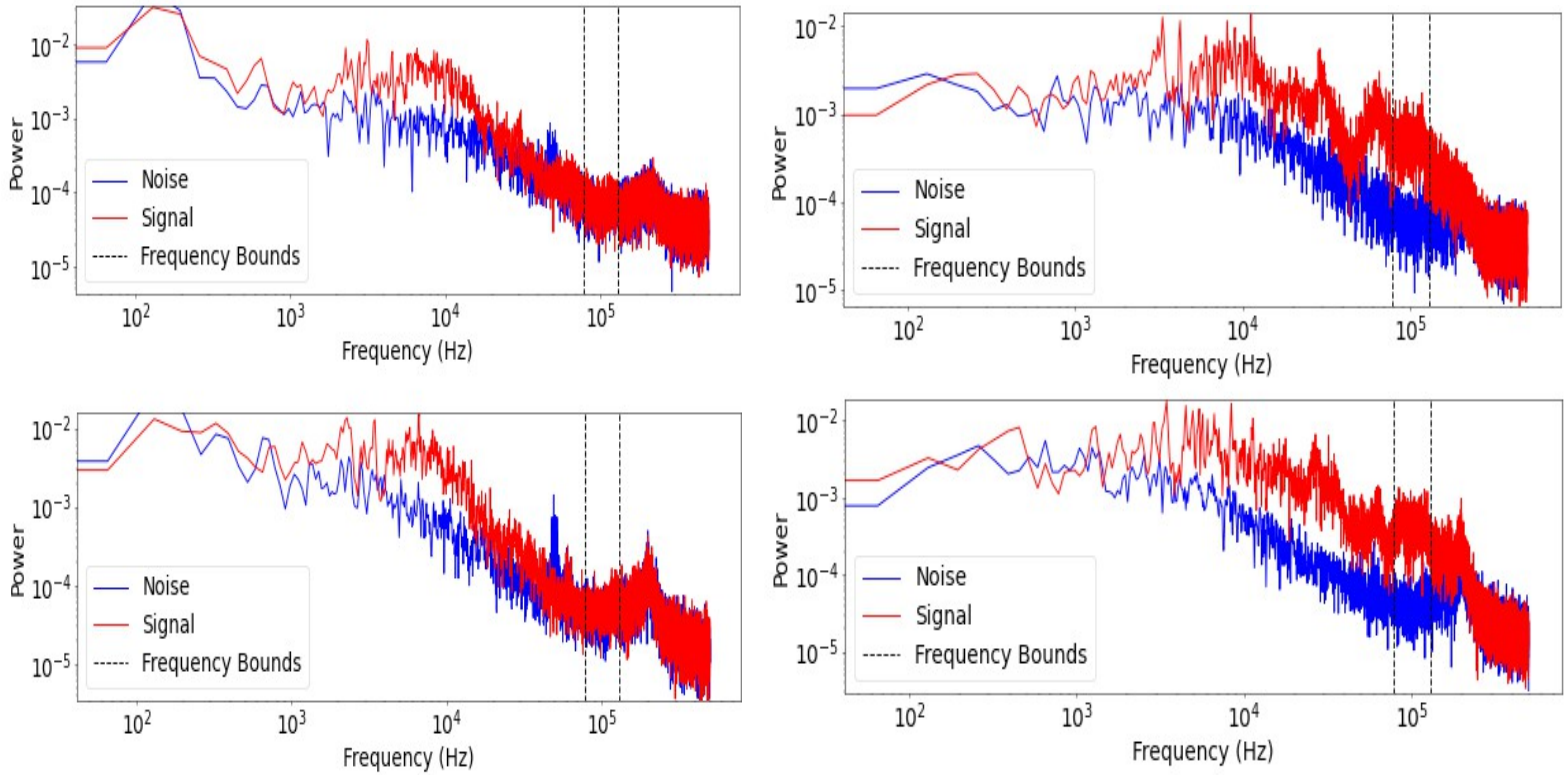





*(Above) PICO-60 bubble chamber schematic.*

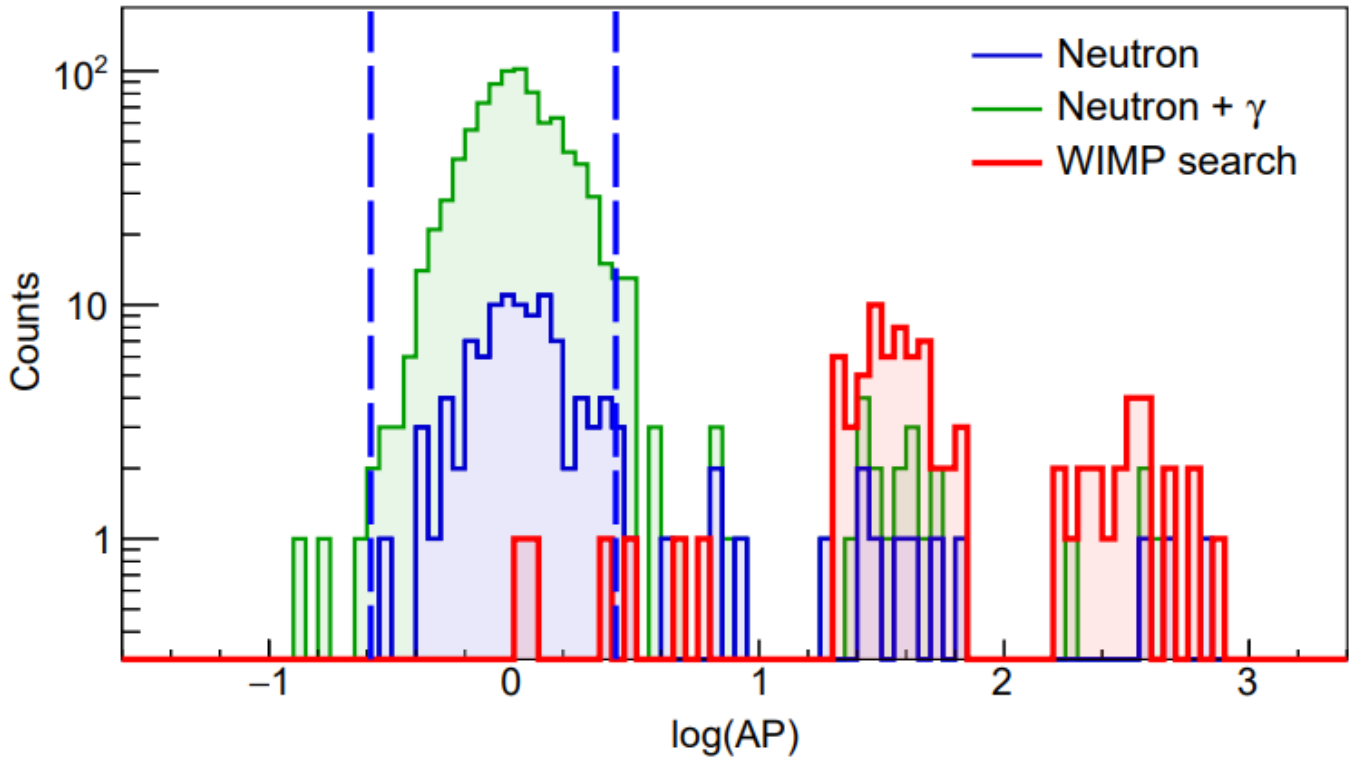
- PICO-60 operated at SNOLAB, filled with 52kg of $C_3F_8$.
- 1404 kg-day blind exposure at 2.45 keV produced 87 bulk single-bubble events during the WIMP search.
- Set constraint of $2.5 \cdot 10^{-41}$ cm$^2$ for a 25 GeV WIMP.
  - Achieved by using Acoustic Parameter (AP), calculated as the difference in signal to noise in high frequencies for alpha discrimination.
  - This analysis found 3 nuclear recoils and 3 "mid-AP" events.

# PICO-60 AP Analysis




*(Left) Power spectra of nuclear recoil vs (Right) Alpha from $^{222}Rn$ decay*

# PICO-60 AP Analysis

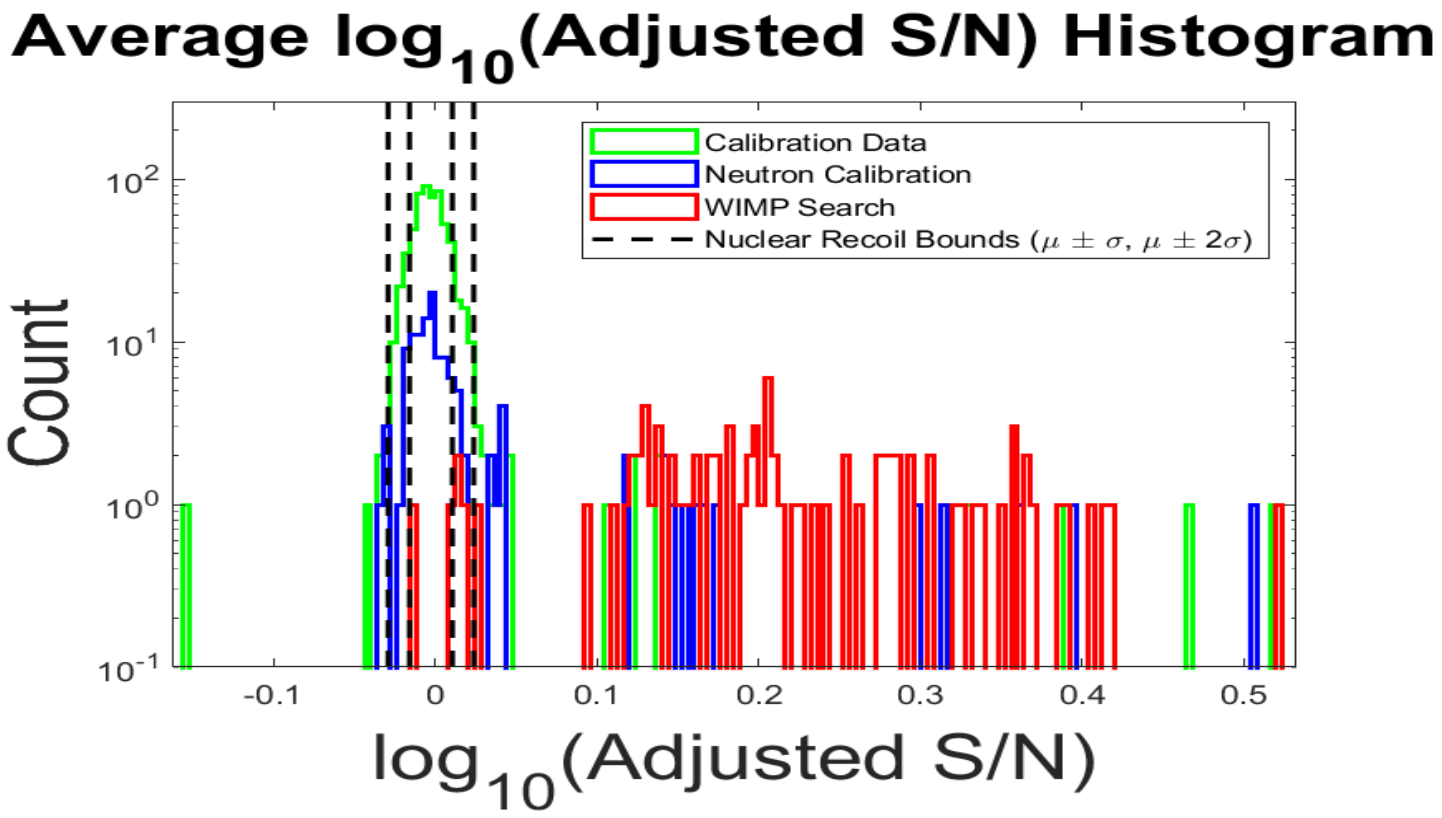



*Logarithm of AP from initial analysis of PICO-60 complete exposure, with bounds from -3σ to +2σ for nuclear recoils (in blue). Taken from arXiv:1902.04031 [astro-ph.CO].*

## Signal to Noise Ratio Analysis

- Wanted to test how the ratio of signal to noise power spectra (SNR) compared to AP in alpha discrimination.
  - My introduction to acoustic analysis at PICO
- Used more frequency bands than AP analysis to improve resolution.
- Was able to classify 2 of the "mid-AP" events as nuclear recoils to $2\sigma$ confidence.
  - One event was still unable to be classified.

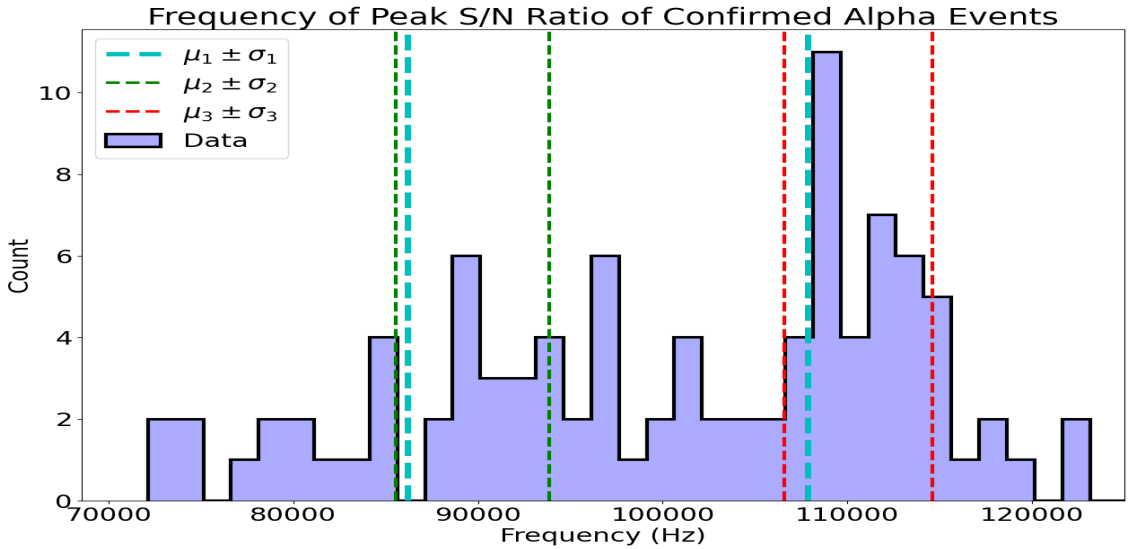
Signal to Noise Ratio Analysis




*Logarithm of "adjusted" SNR, with ±2σ bounds highlighted (in black).*

- Improved results from additional frequency bands presents the problem of selecting "ideal" bands.
- In bimodal statistics, a "mixture" of two distributions is bimodal iff the separation d > 1, where $d = \frac{|\mu_1 - \mu_2|}{2\sqrt{\sigma_1 \sigma_2}}$ .
- The resolution of a distribution R is defined as $R = \frac{\sigma}{\mu}$.
- We ideally want to maximize d and minimize R.
  - Same as maximizing "goodness" $G = \frac{d}{R}$.

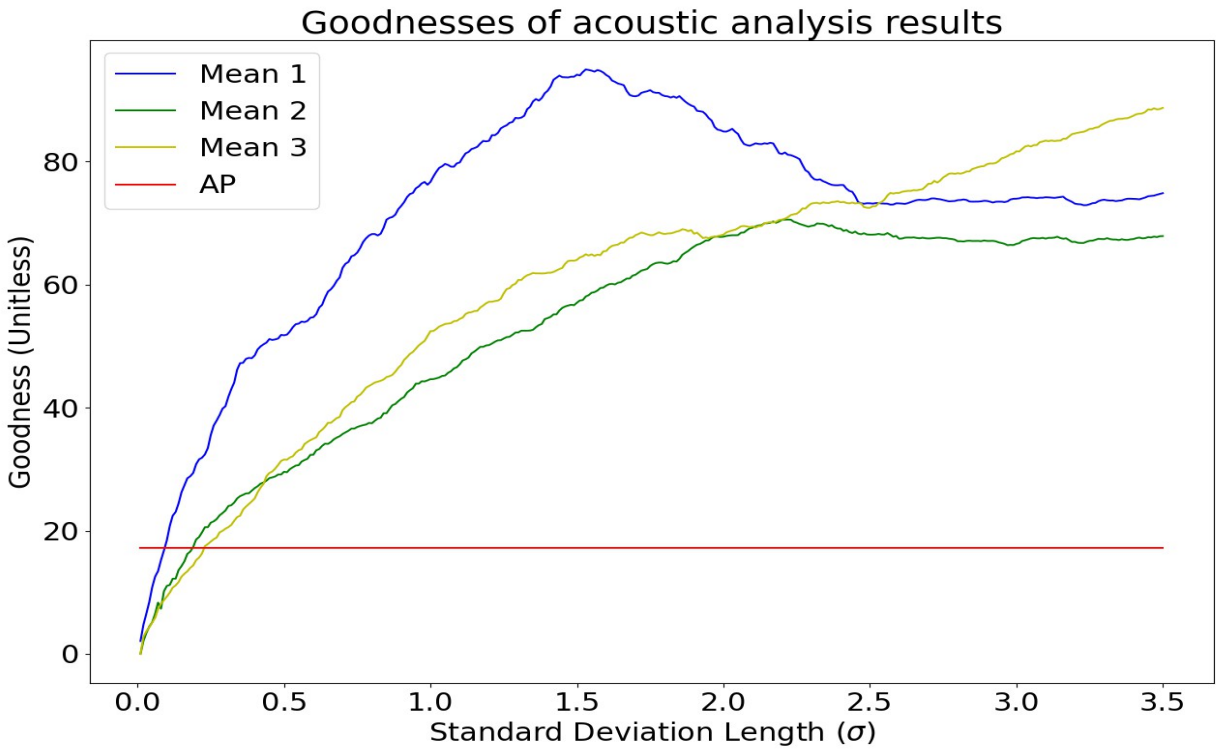
- Using AP to find alphas and then investigating the strongest frequency in the signal also produces a bimodal distribution.
  - Gives us somewhere to start!



## Statistical Analysis Algorithm

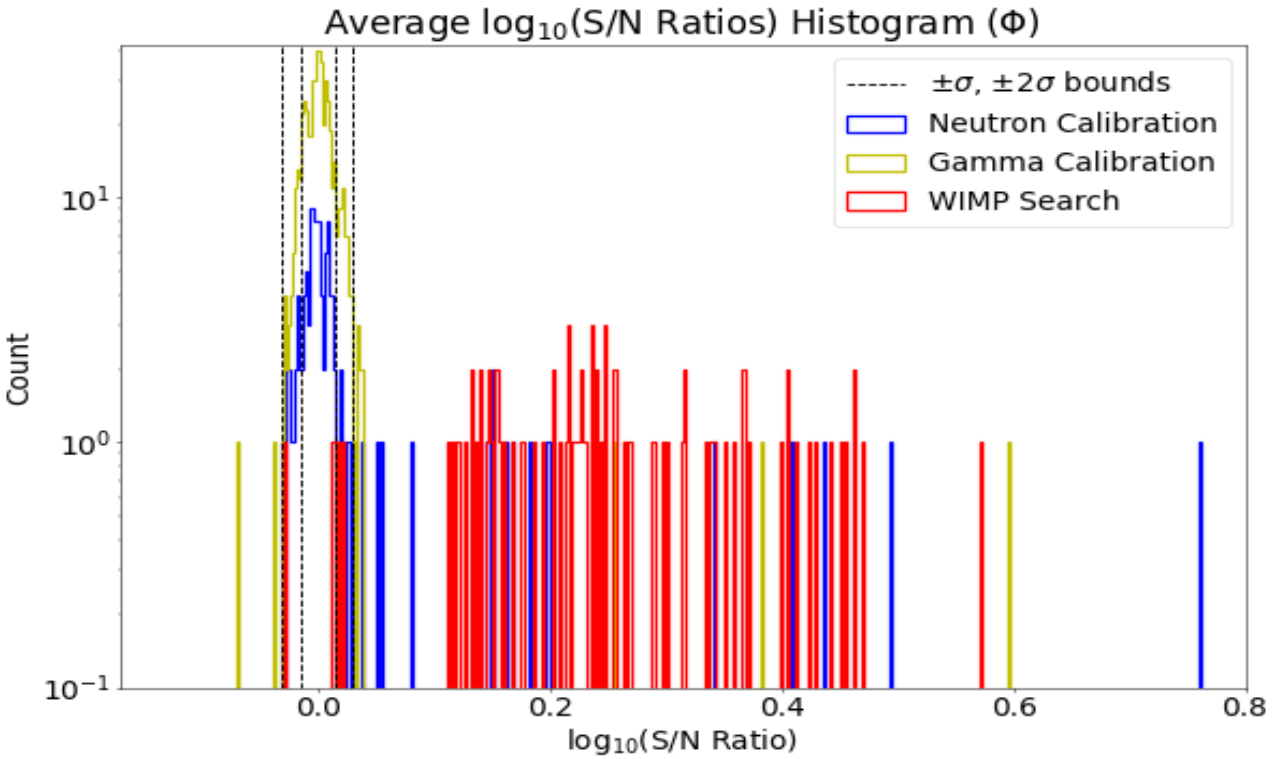
- Using each of the 3 indicated means and standard deviations, we can find a center for our desired frequency bands, and expand out in multiples of $\sigma$.
  - Smaller multiples of $\sigma$ improve accuracy but require more computational power.
- For each band we can perform the SNR analysis to calculate d, R, and G, and select the band that maximizes G to classify the WIMP search events.

## Statistical Analysis Algorithm




*Goodness of SNR Distribution vs number of standard deviations σ*

## Statistical Analysis Results



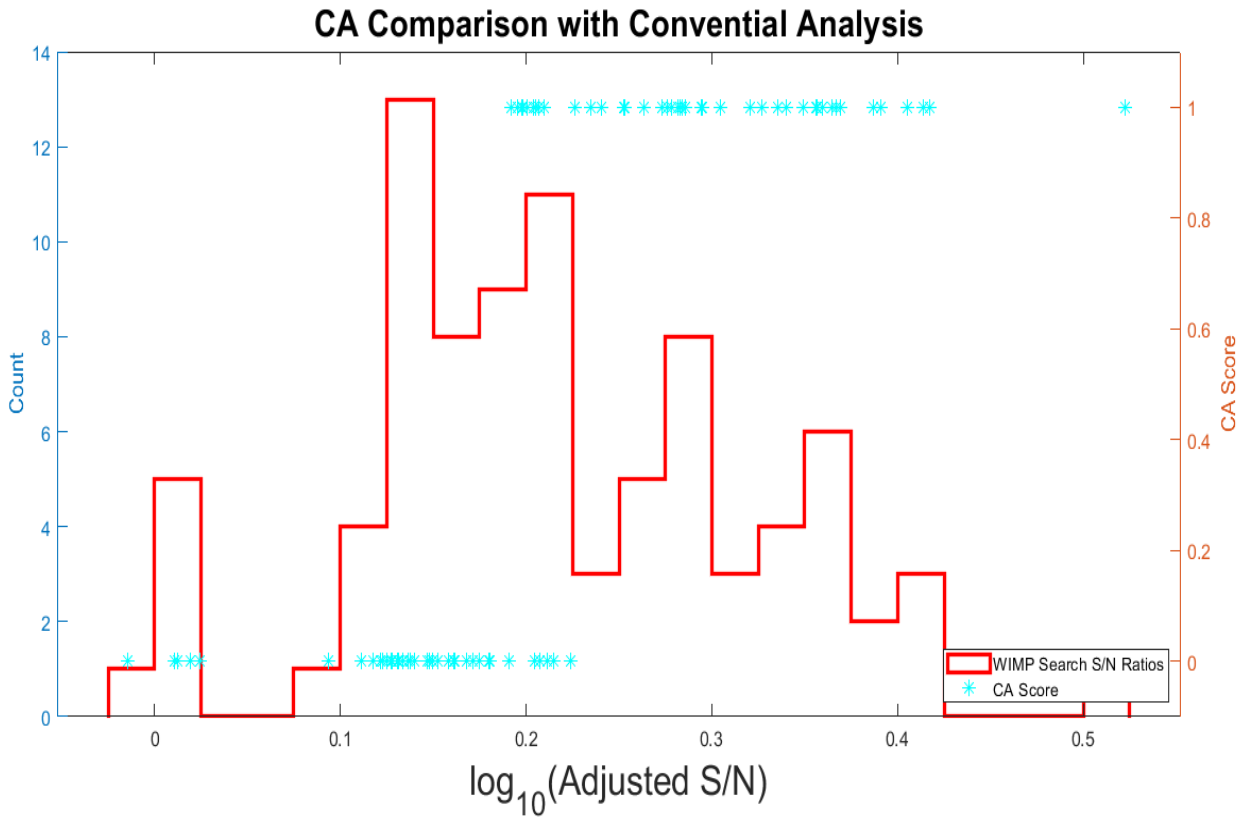

*Logarithm of "adjusted" SNR, with ±2σ bounds highlighted (in black).*

## Conventional Algorithm (Recap)

- Calculate AP as done in prior analysis
- Use AP to find high-confidence alpha events, investigate the distribution of peak SNR frequencies in these events.
- For each mode, use SNR analysis to investigate how G changes as a function of $\sigma$.
- Select the peak frequency band to use for final SNR analysis.

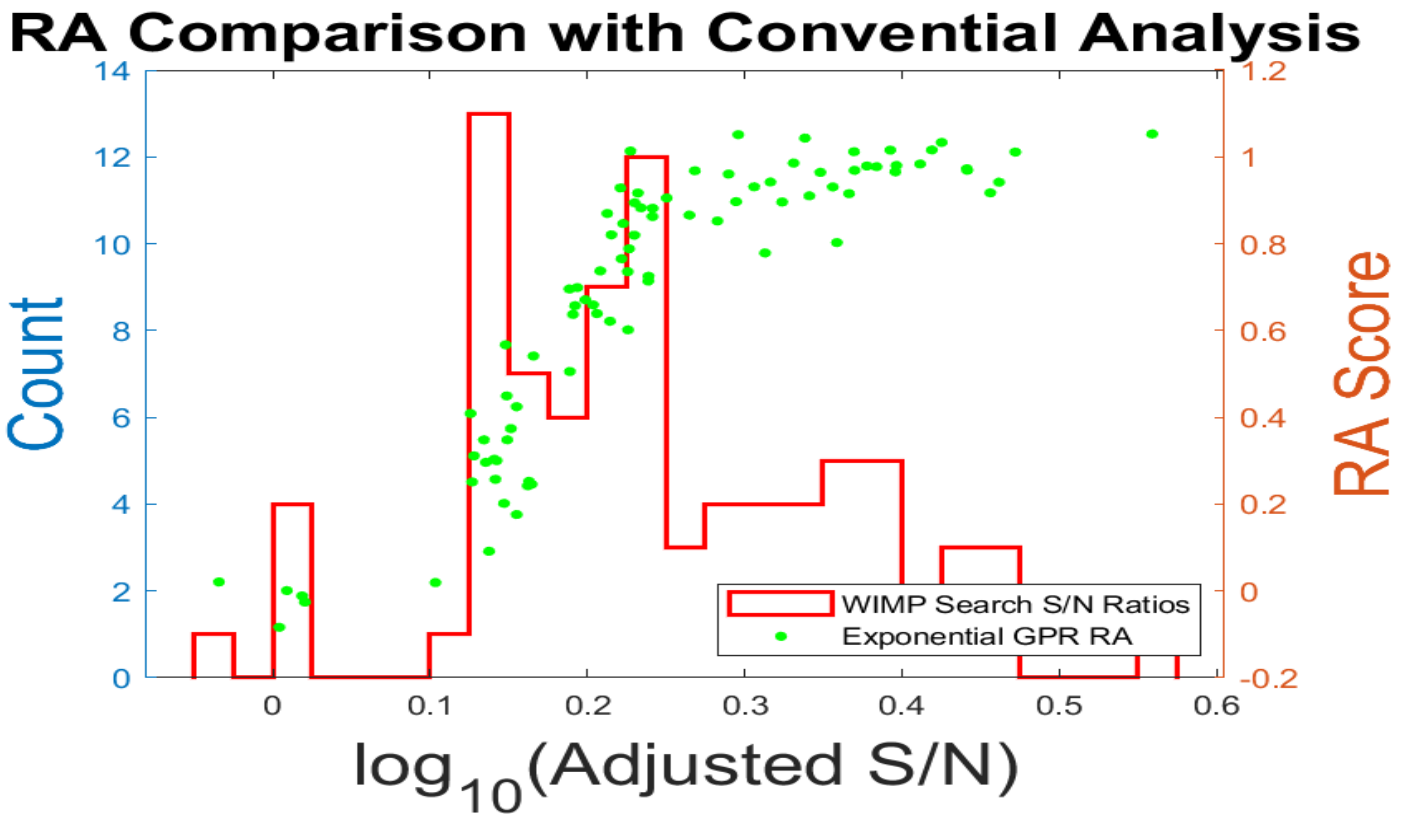
- Using MATLAB Classification Algorithms (CAs) and Regression Algorithms (RAs) presented promising results for using Machine Learning to classify WIMP search events.
- Coarse and Exponential Gaussian Processes, and k-nearest neighbours algorithms both followed increasing trends with AP and SNR, which is a good start.
  - Still less useful than conventional analysis...

# MATLAB CA Results




*kNN Scoring vs log(SNR)*

MATLAB RA Results

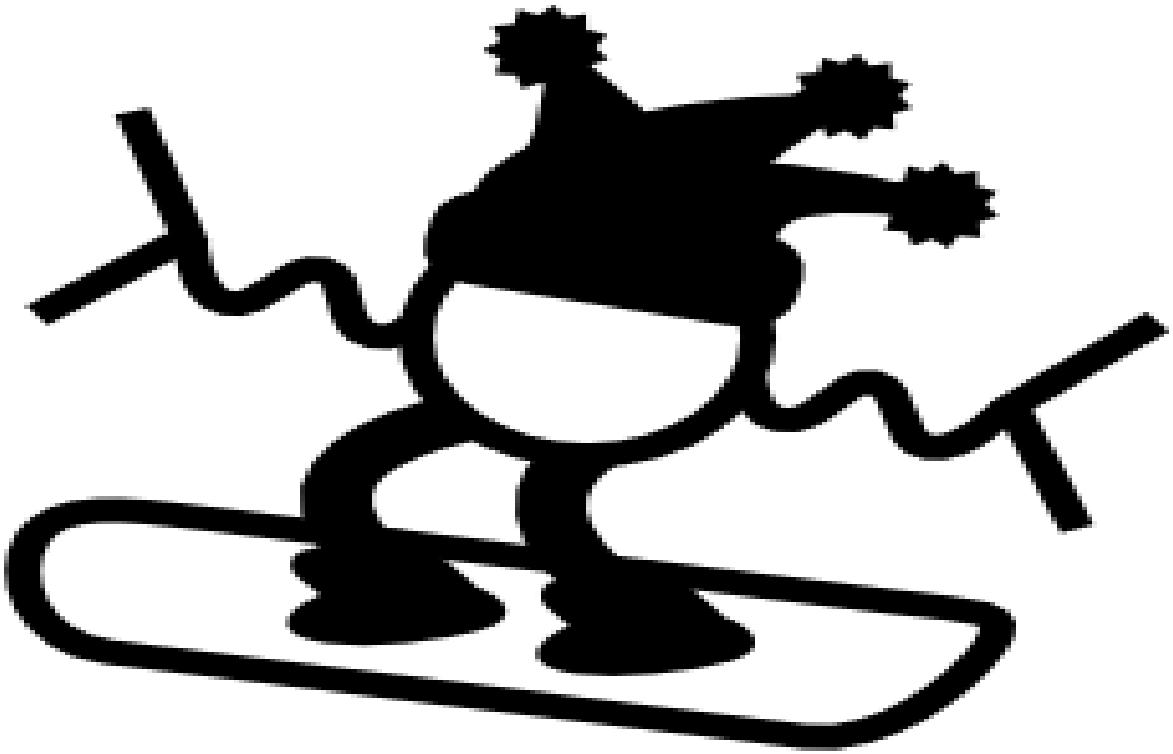



*Exponential Gaussian Process Regression score vs log(SNR)*

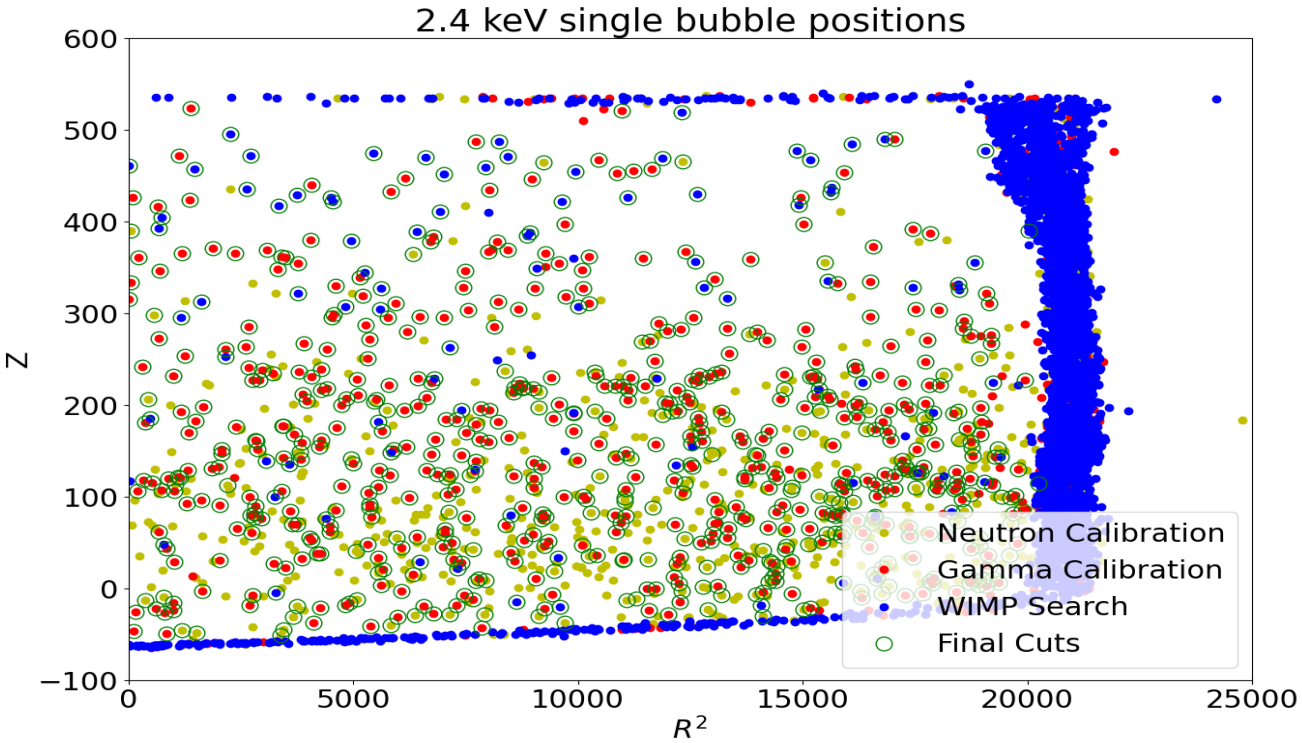
- Python's sklearn provides many similar algorithms as MATLAB, as well as Principle Component Analysis (PCA) to discard parameters that don't help with alpha discrimination.
  - These algorithms can be “optimized” for high agreement with calibration data before use on WIMP search data.
- De-noising algorithms and PCA may also be useful for acoustic analysis.

## Next Steps

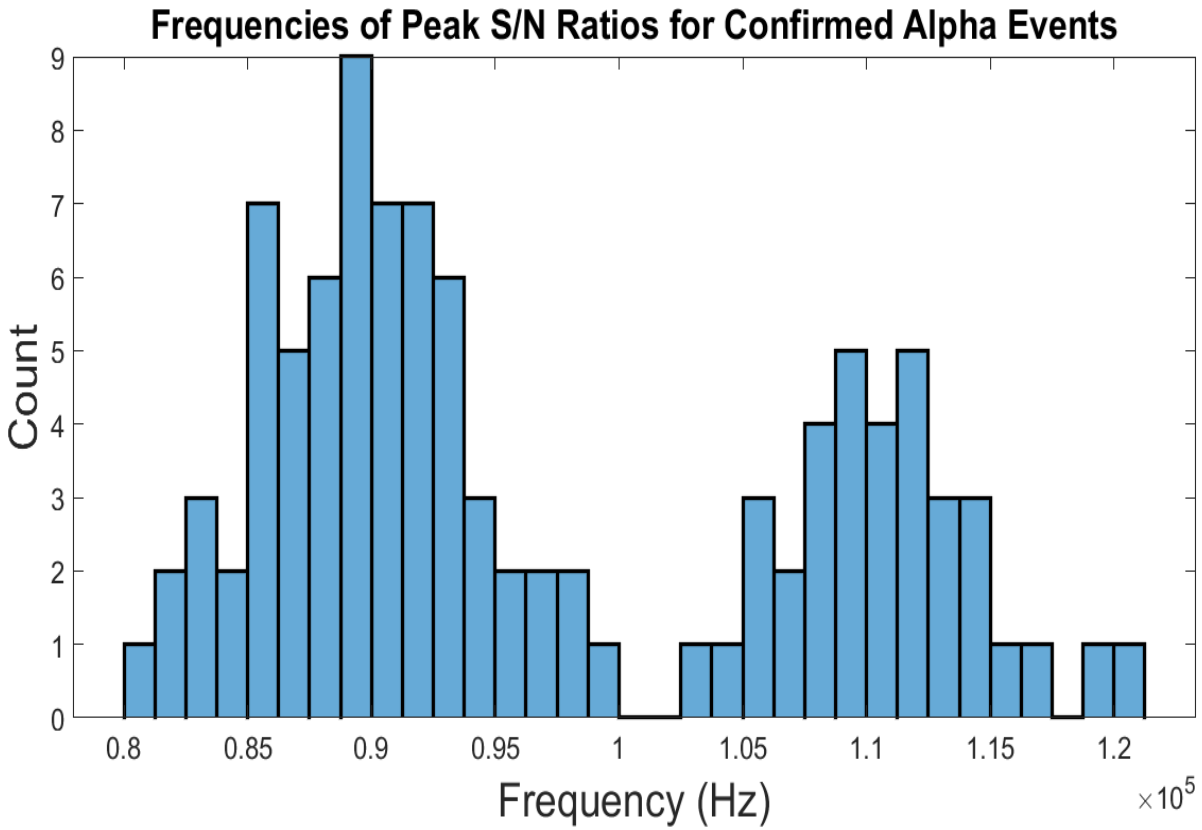
- Incoming data from PICO-40L can be used to generalize acoustic analysis algorithm to more PICO chambers.
  - Making this algorithm effective for PICO-40L was the original motivation.
- sklearn algorithms present themselves as a supplement to results from conventional analysis.
- PCA and de-noising algorithms can be incorporated into current analysis algorithm to improve results.



*Thanks for listening!*

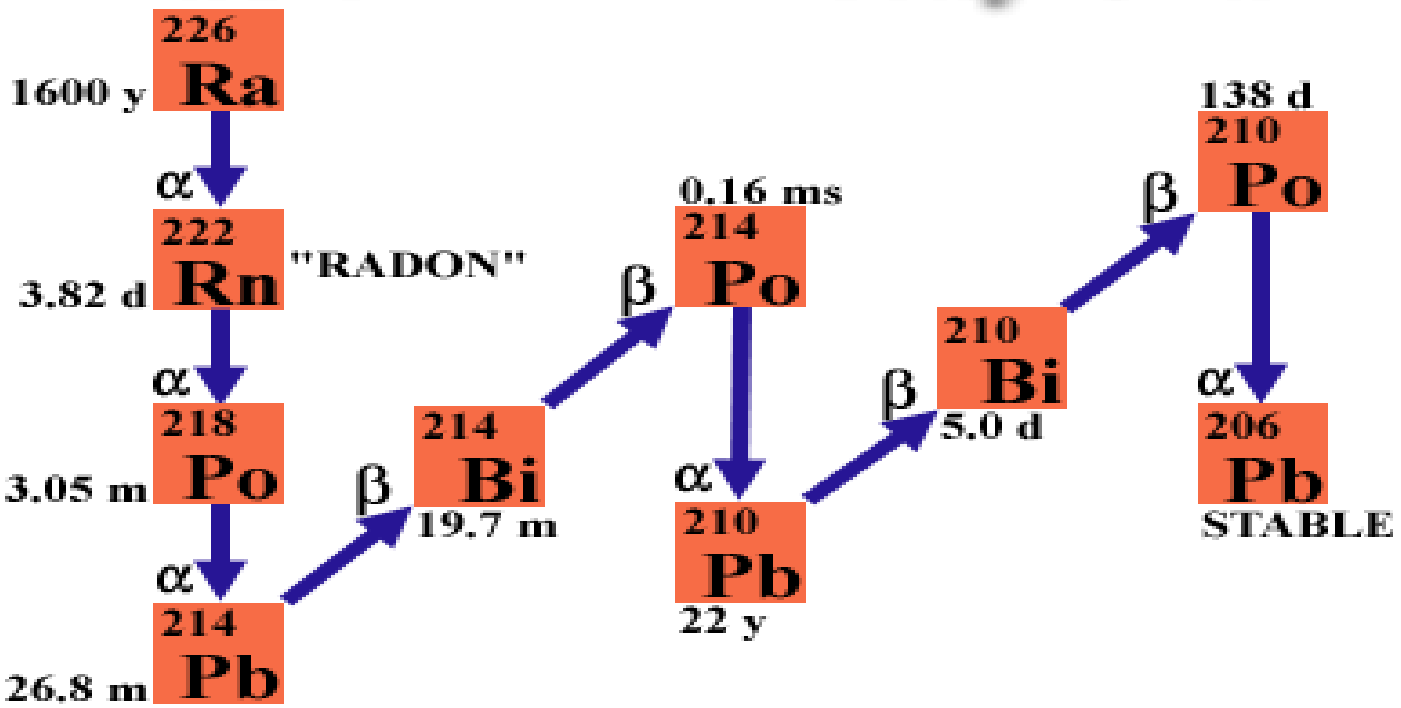



*Events in PICO-60 Complete Exposure*

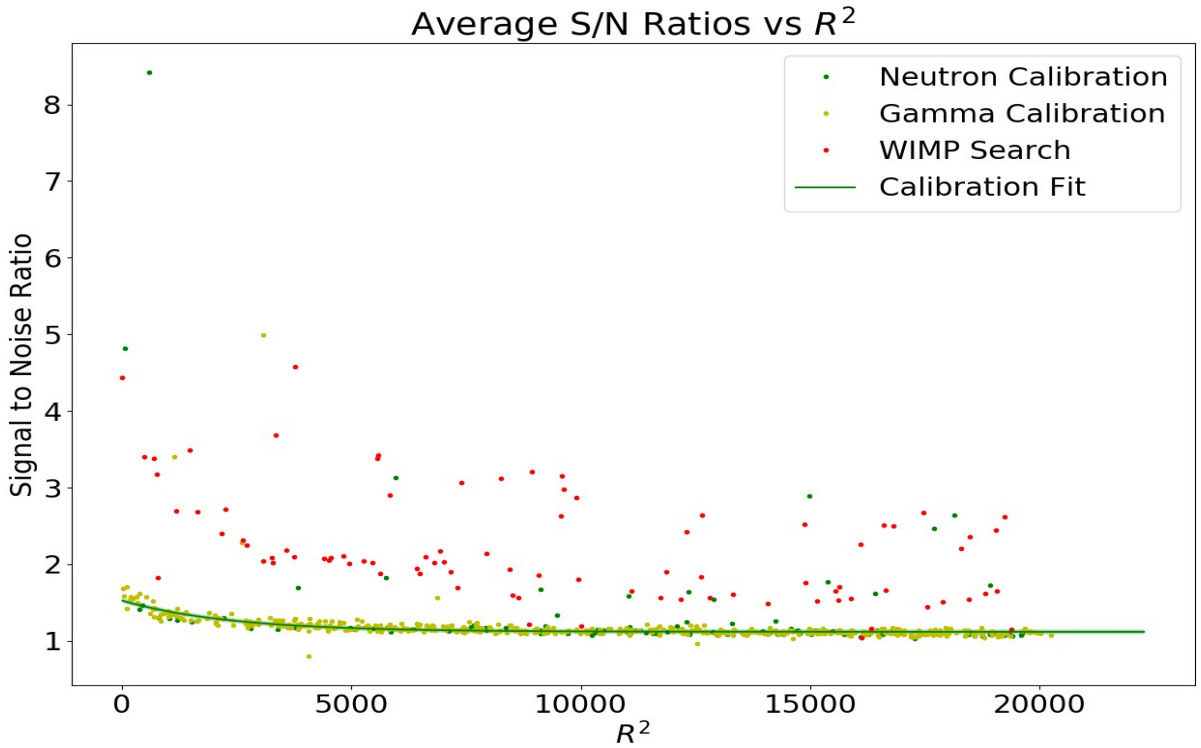



*Original Frequency Histogram produced in MATLAB*

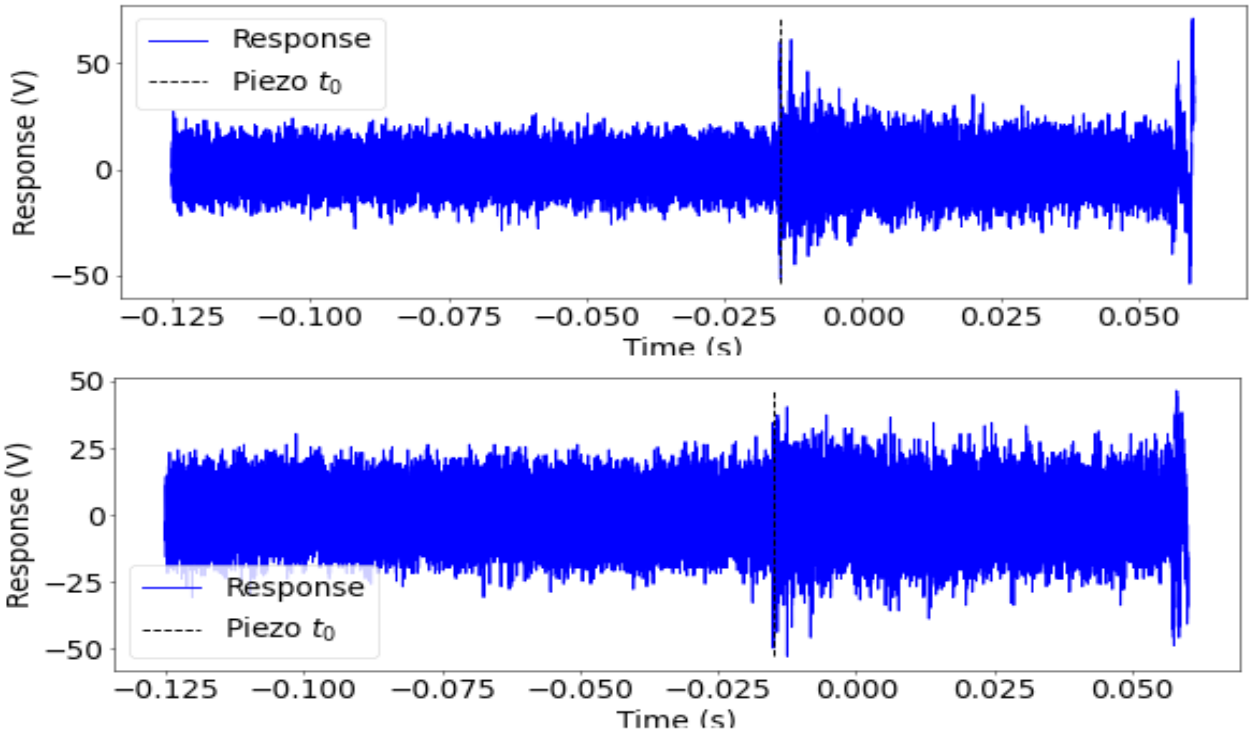
# Radium-226 Decay Chain



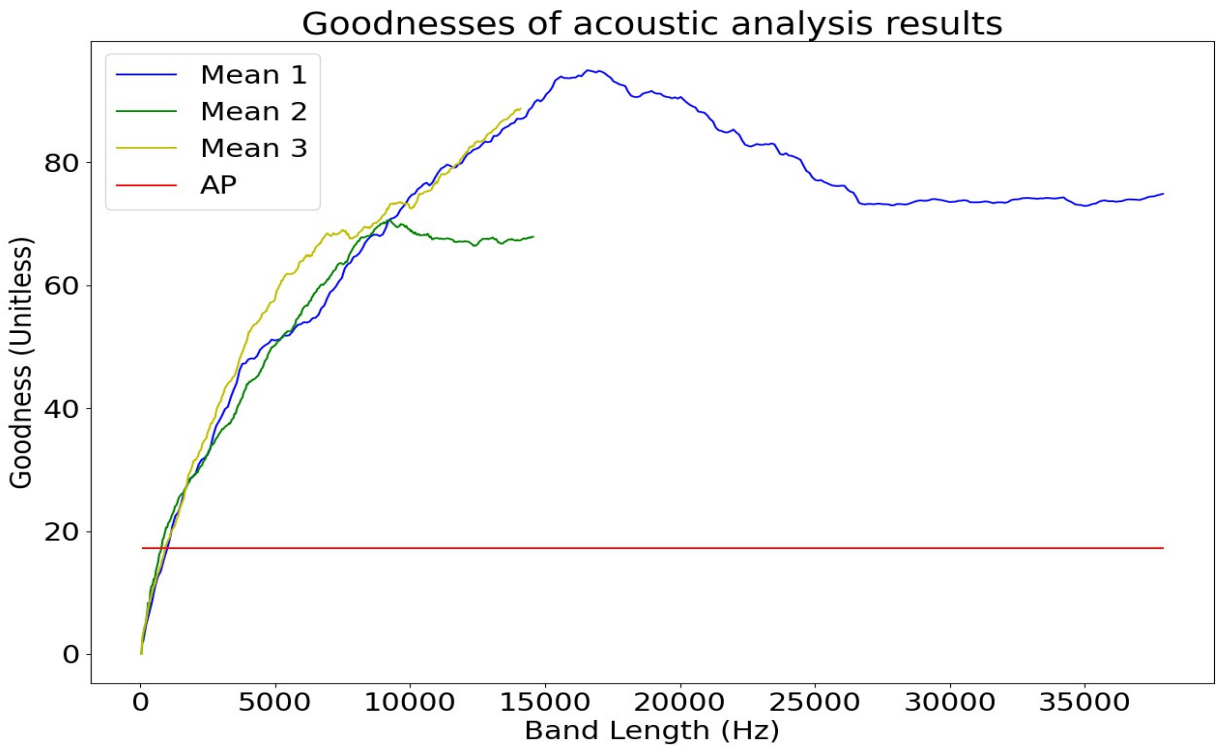

*$^{226}$Rn decay chain (taken from https://www.nist.gov/image-23773)*



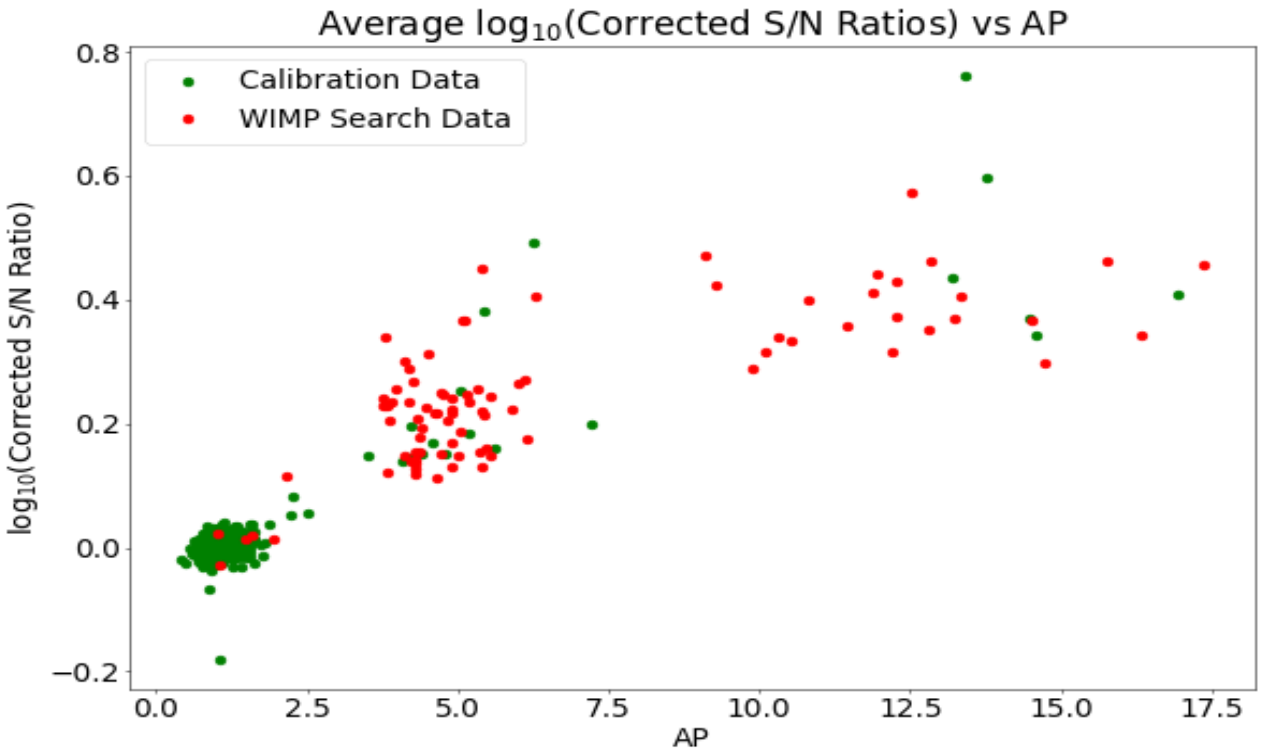

*$R^2$ Correction for SNR*




*Piezoelectric response in single-bubble bulk neutron calibration event*




*Goodness plot in terms of raw band length (rather than number of standard deviations).*




*Bubble plot comparison of SNR analysis with AP.*