Australian National University

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Intrinsic Background Characterisation Of An Ultra-pure NaI Test Crystal For SABRE South

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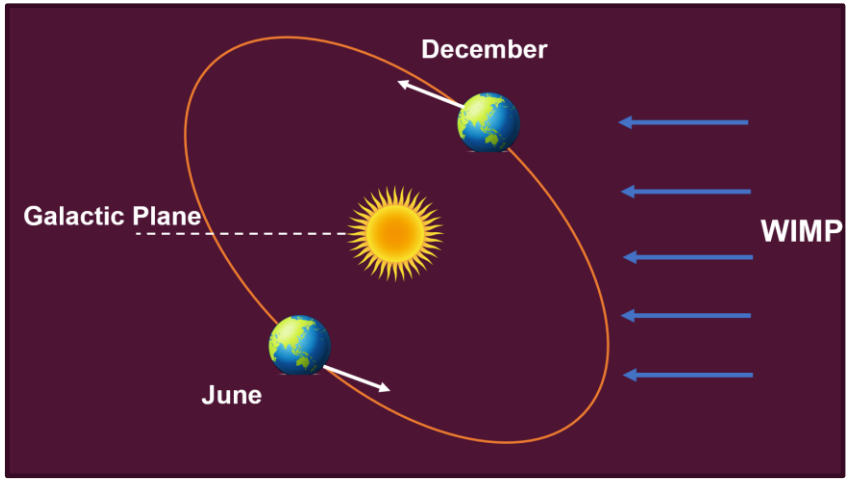
ON BEHALF OF THE SABRE SOUTH COLLABORATION

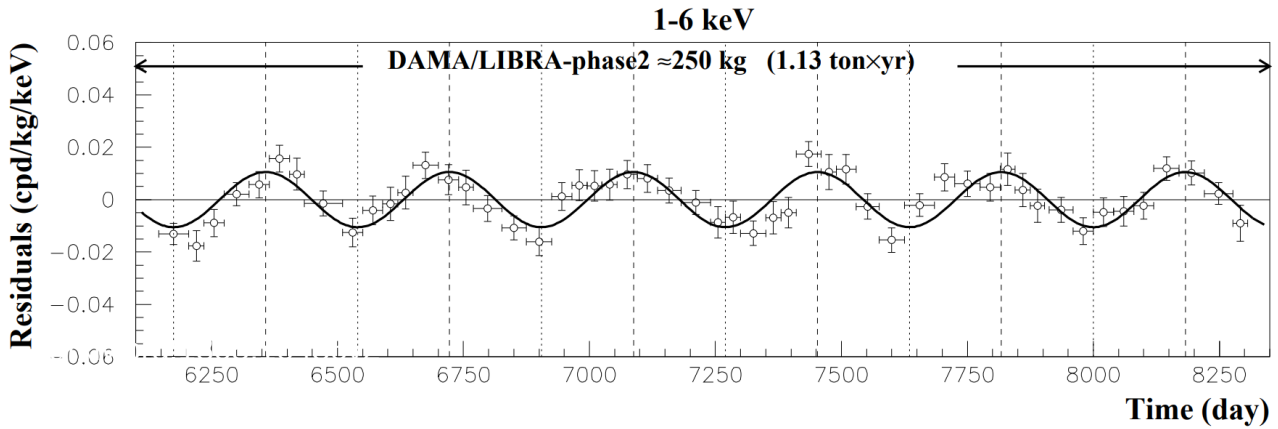
15 DECEMBER 2022

DARK MATTER CASE

- DAMA/LIBRA only experiment to claim a DM signal - in the form of Weakly Interacting Massive Particles (WIMPs)
  - NaI(Tl) targets
- Annual modulation is approximately 0.01 cpd/kg/keV

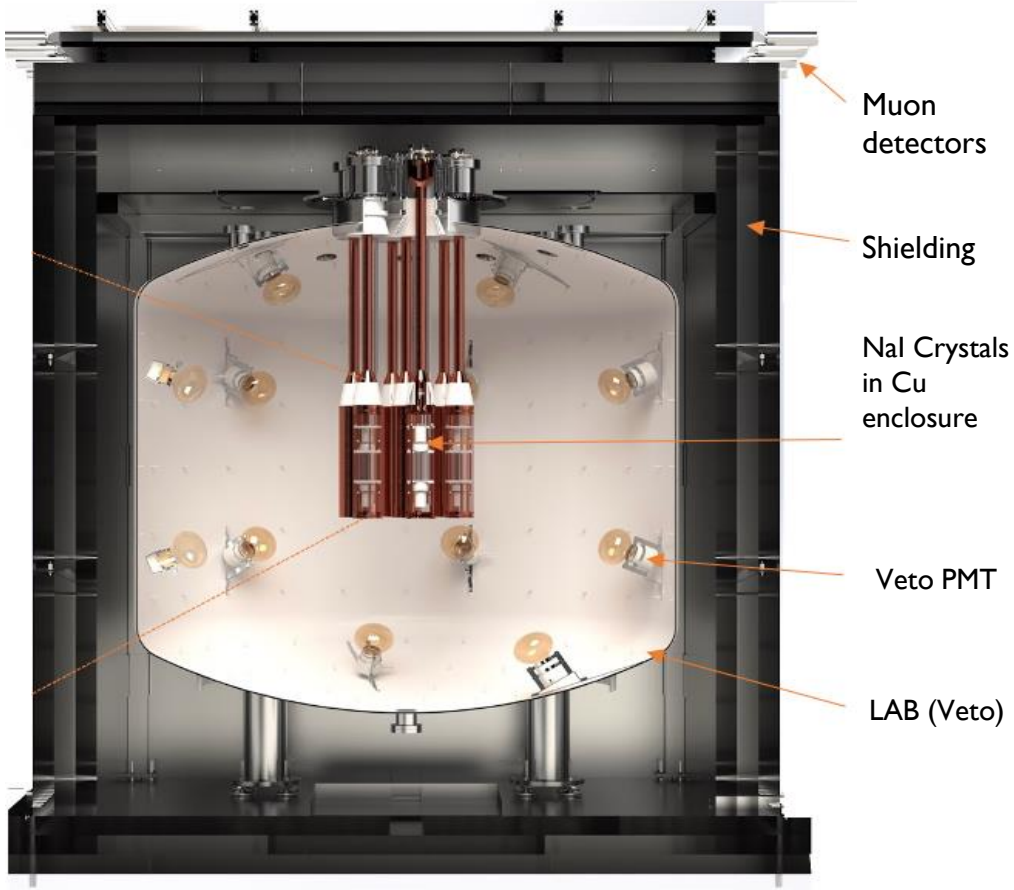


WIMP Wind peak in June – toward wind
WIMP Wind low in December – away from the wind



SABRE SOUTH

- ANAIS, COSINE and SABRE
  - COSINUS Cryogenic NaI
- Sodium iodide with Active Background Rejection (SABRE) South part of SABRE international collaboration
  - To be placed in Stawell Underground Physics Laboratory (SUPL), Victoria
- Annual modulation ~ 0.01 cpd/kg/keV,
  - background expected :1 cpd/kg/keV in the 1-6 keV region of interest
- SABRE focusing on development of ultra-pure NaI
- Characterisation of intrinsic backgrounds important - eg ^{238}U, ^{232}Th, ^{210}Pb, ^{40}K
  - Expected in the ~ ppb levels



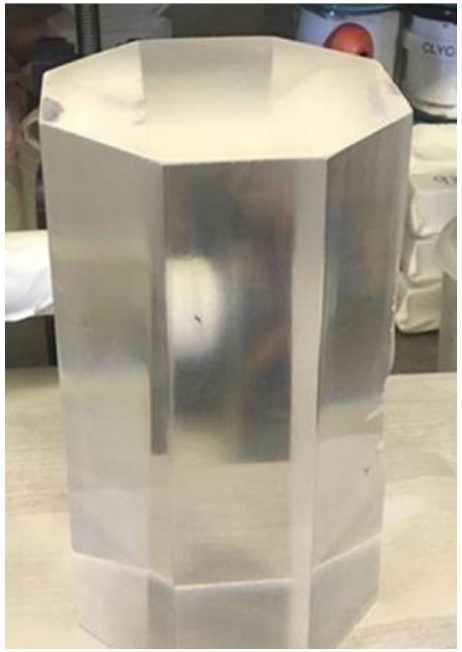
Presented in more detail in I. Bolognino's talk on Wednesday 4pm.

SABRE CRYSTALS

NaI-033

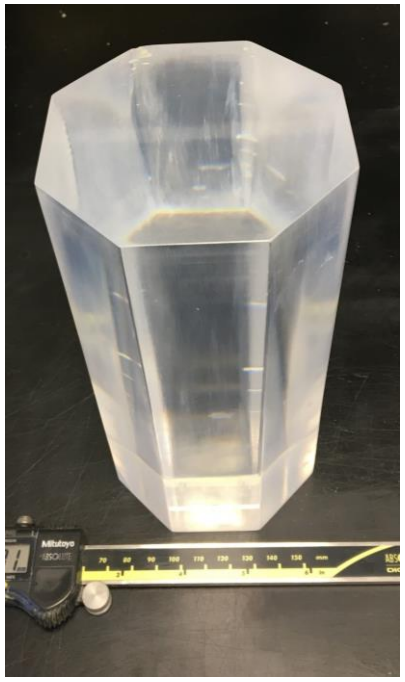
First crystal characterised

- Grown by Princeton University and RMD
- 3.4 kg
- Counted at LNGS, Italy.



NaI-035

- Grown by RMD
- 3.7 kg

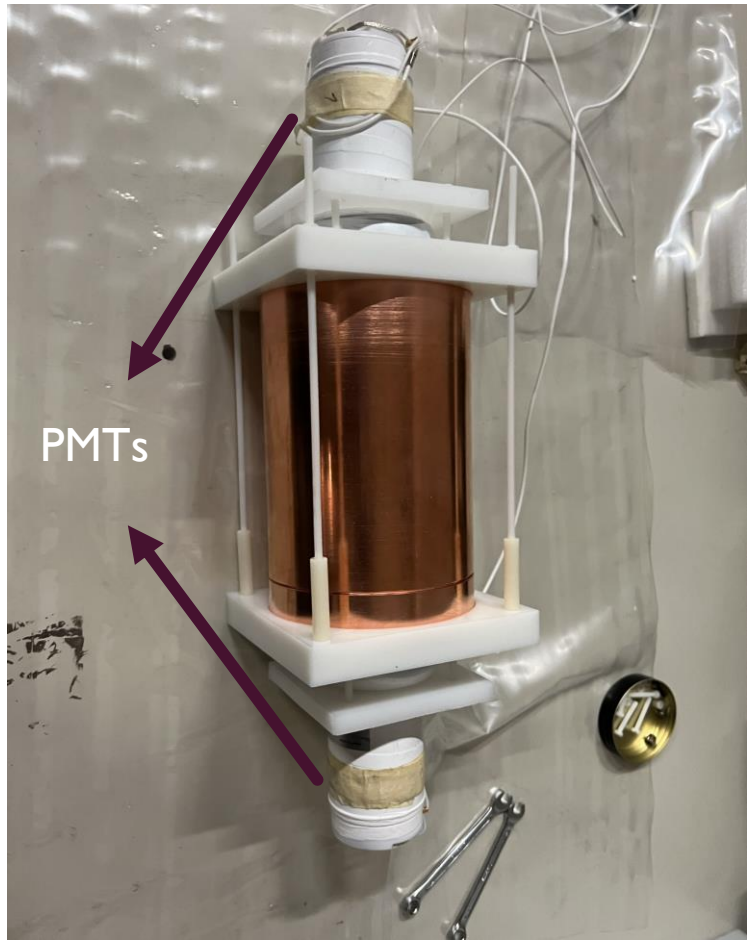


NaI-037

- Grown RMD
- 3.4 kg
- Sent to LNGS, Italy.

NAI-035

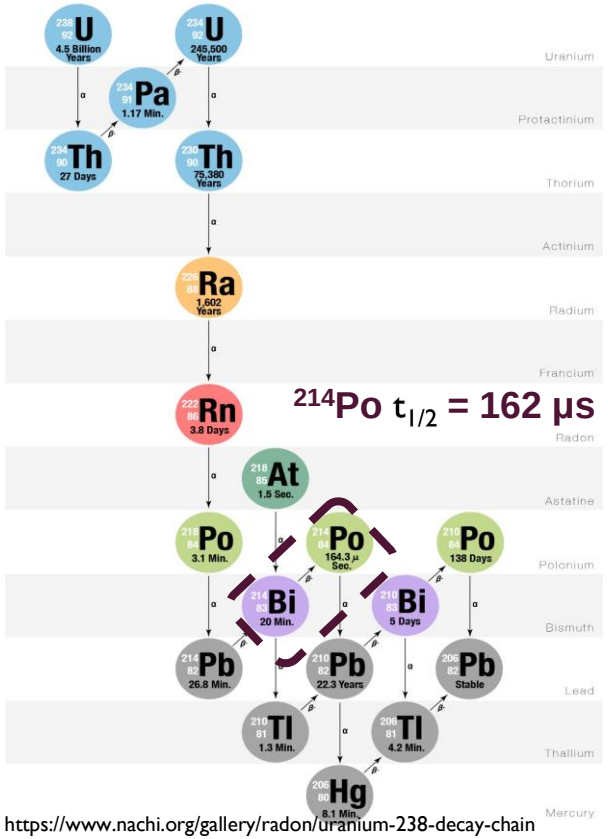
- Set-up to measure backgrounds in LNGS, Italy
- Crystal encapsulated and wrapped in reflective material
- 2 x Hamamtsu 3” 11065 PMTs
- Two sets of runs since May 2022:
  - Low Gain
  - High Gain
- This work: Characterisation ^{238}U and ^{232}Th using BiPo decays in NaI-035



BIPO DECAY

"Slow BiPo"

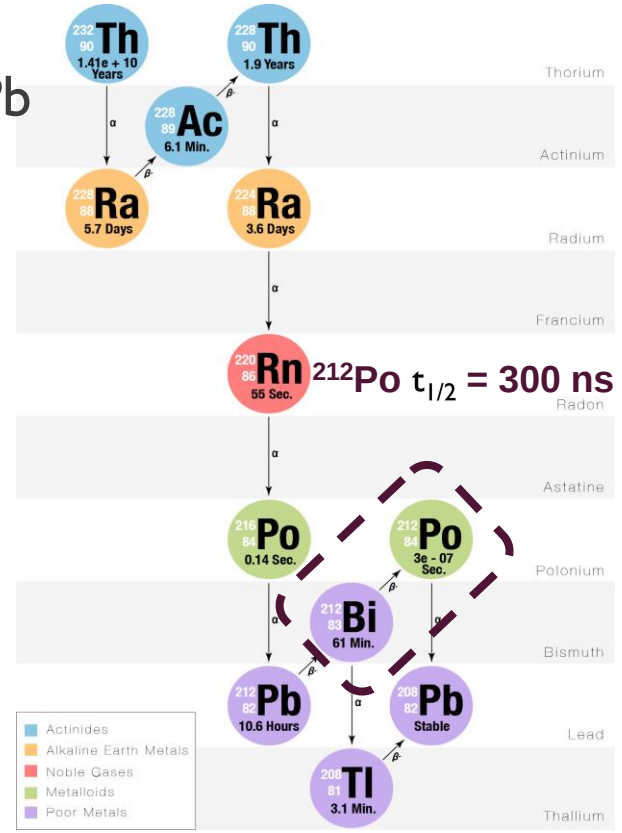
$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$



https://www.nachi.org/gallery/radon/uranium-238-decay-chain

"Fast BiPo"

$^{212}Bi \xrightarrow{\beta} {}^{212}Po \xrightarrow{\alpha} {}^{208}Pb$



https://www.nachi.org/gallery/radon/thoron-decay-chain

SLOW BIPO

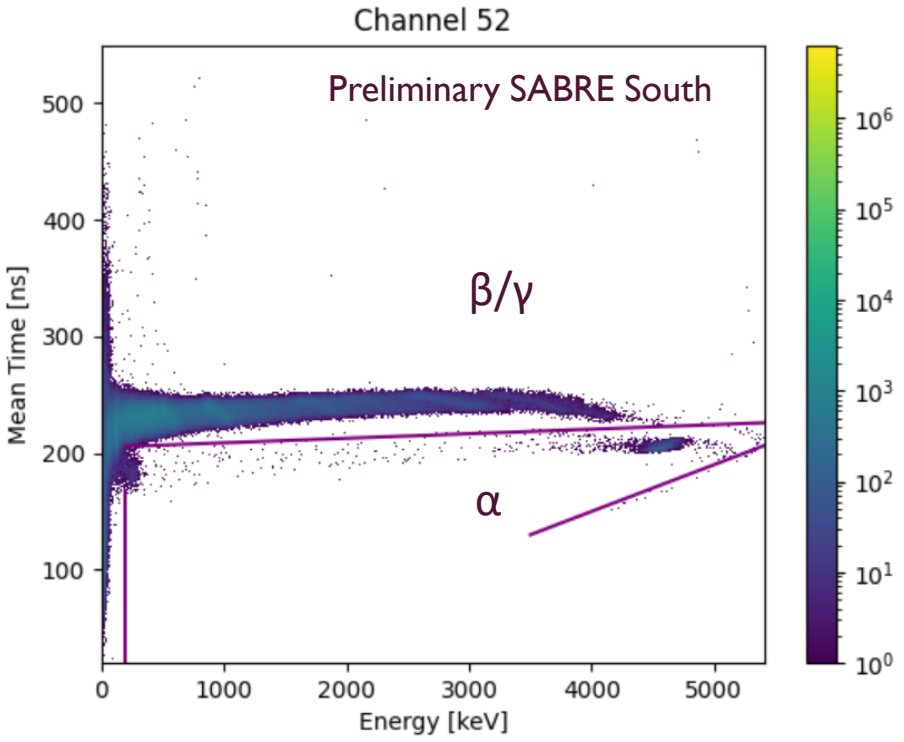
- Looking for β followed by an α with $t_{1/2}$ = 162 μs
  - Digitiser recording window = 5 μs
  - Two events in quick succession
- NaI has pulse shape discrimination:
  - Different integrated **charge** deposit – alphas more energy deposit
  - Different **amplitude weighted mean times**

$$\text{Amplitude weighted mean time } \langle t \rangle_{600} = \frac{\sum_{t_i < 600 \text{ ns}} h_i t_i}{\sum_{t_i < 600 \text{ ns}} h_i}$$

SEPARATION OF B/A USING MEAN TIME AND CHARGE

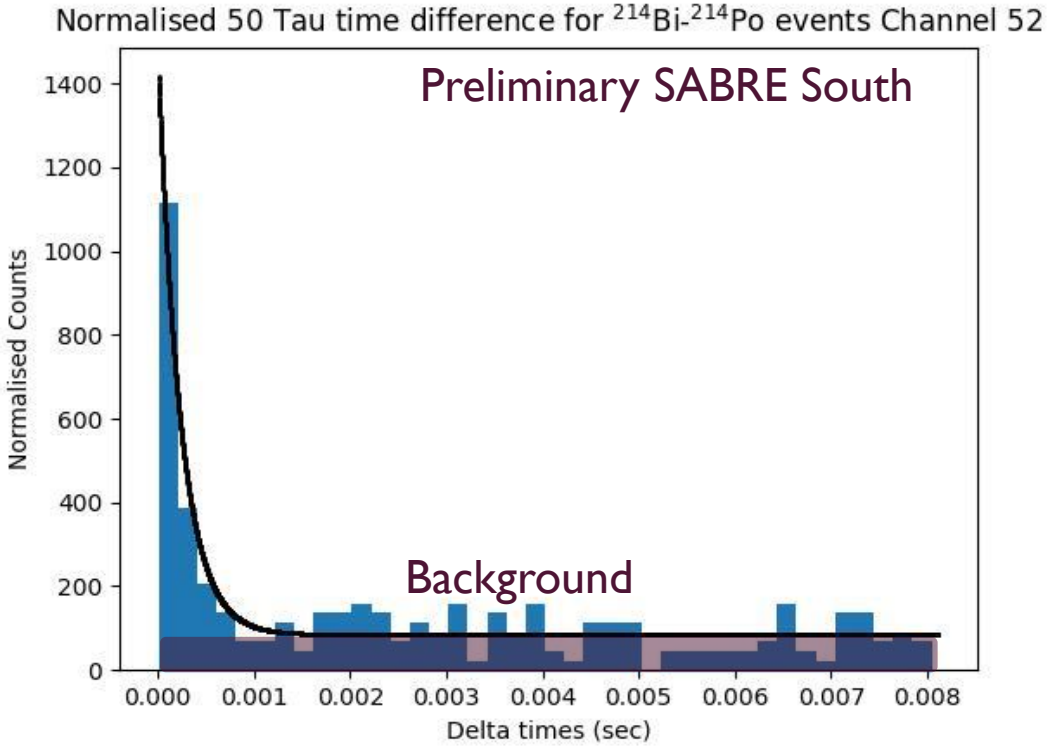
- Prepare cuts and separate β/γ and α
  - Looking at summed unamplified channel

$$\text{Amplitude weighted mean time } \langle t \rangle_{600} = \frac{\sum_{t_i < 600 \text{ ns}} h_i t_i}{\sum_{t_i < 600 \text{ ns}} h_i}$$



TIME DISTRIBUTION MODEL

- Fit range $0 < \Delta(t_\alpha - t_\beta) < \Delta nt_{1/2}$
- Fit data to exponential decay with background
  - $PDF = N\left(1 + Re^{-\lambda t}\right)$
- N can be found by normalising the PDF
- R – ratio of decay component to the background.

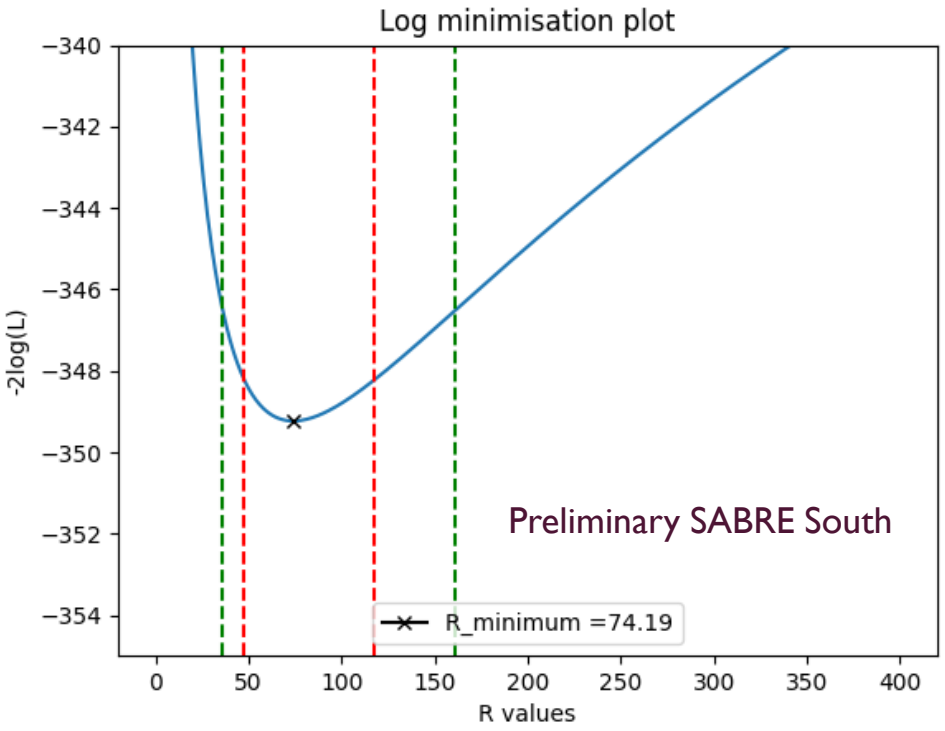


TIME DISTRIBUTION FIT

- Fit range $0 < \Delta(t_\alpha - t_\beta) < \Delta nt_{1/2}$
- Fit data to exponential decay with background
  - $PDF = N(1 + Re^{-\lambda t})$
- R found using likelihood fit

$$L_{max} = \prod(PDF_i)$$
$$L_{min} = -\sum \log(PDF_i)$$

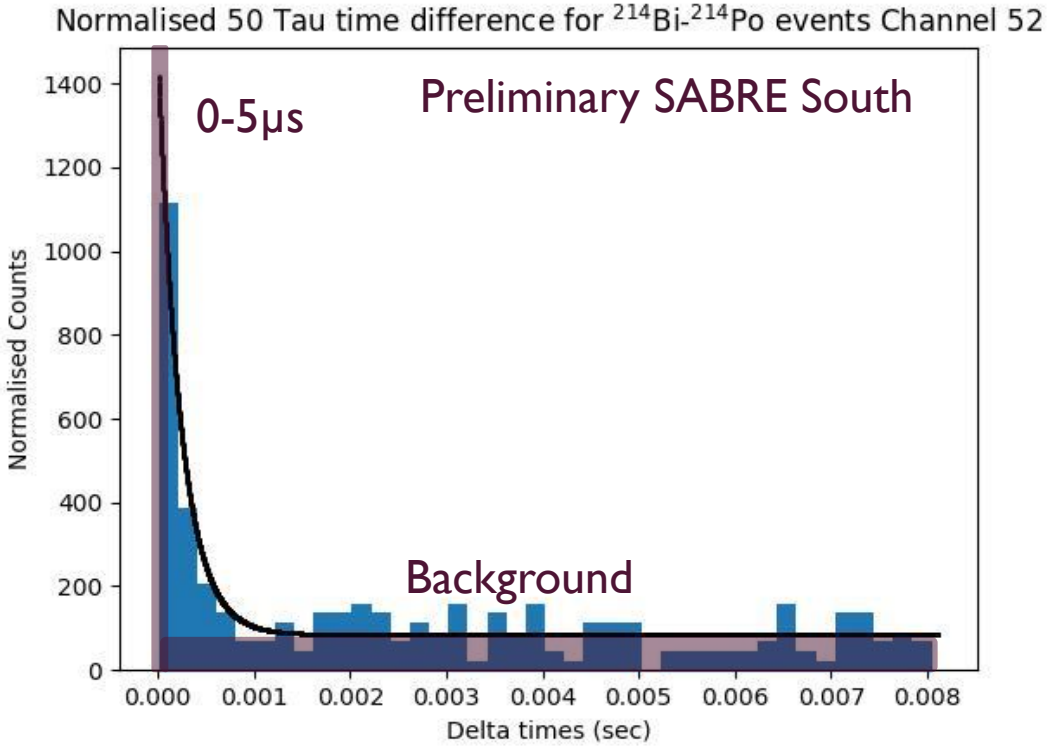
- Fit an exponential to the $\Delta n\tau$ data



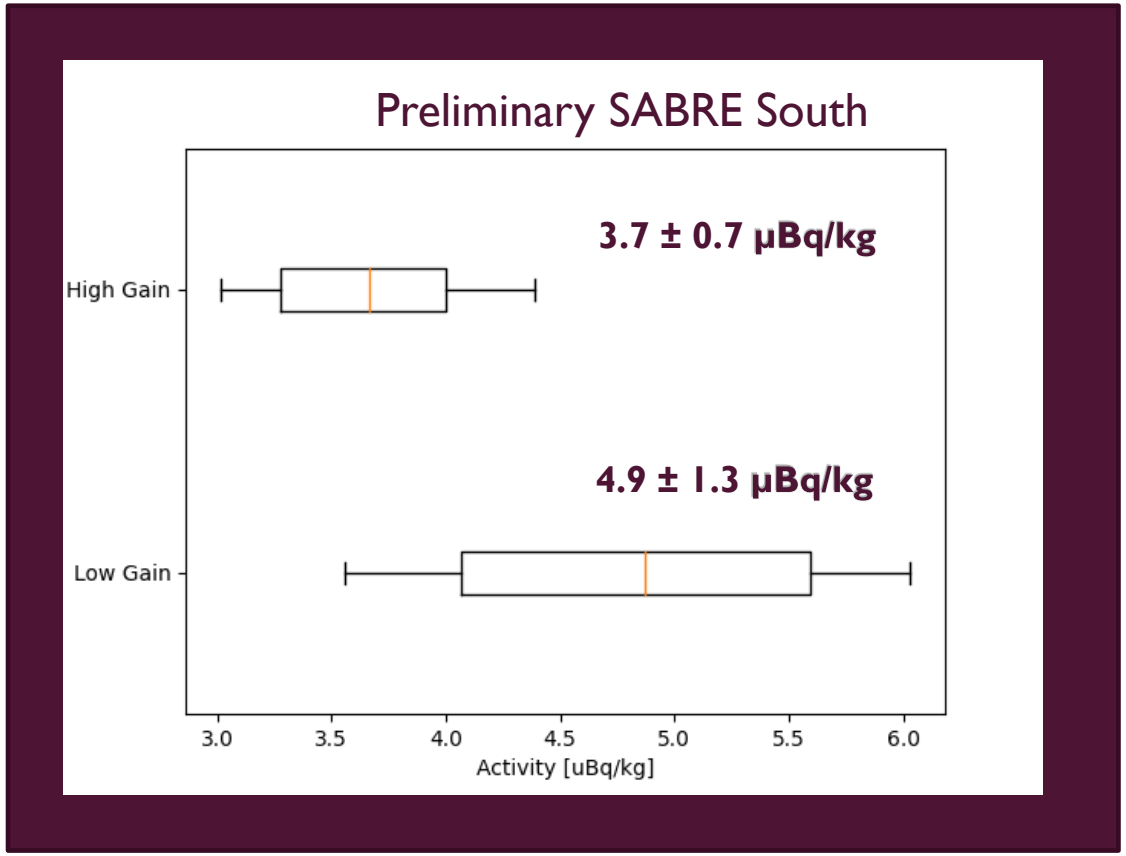
FIND BACKGROUND RATE

- Digitiser collection window = 5μs
  - We could miss BiPo events in this window
  - Fraction missed events

    = 1 - exp(-λ*5μs) ≈ 2%
- Calculate proportion of BiPo decays



RESULTS



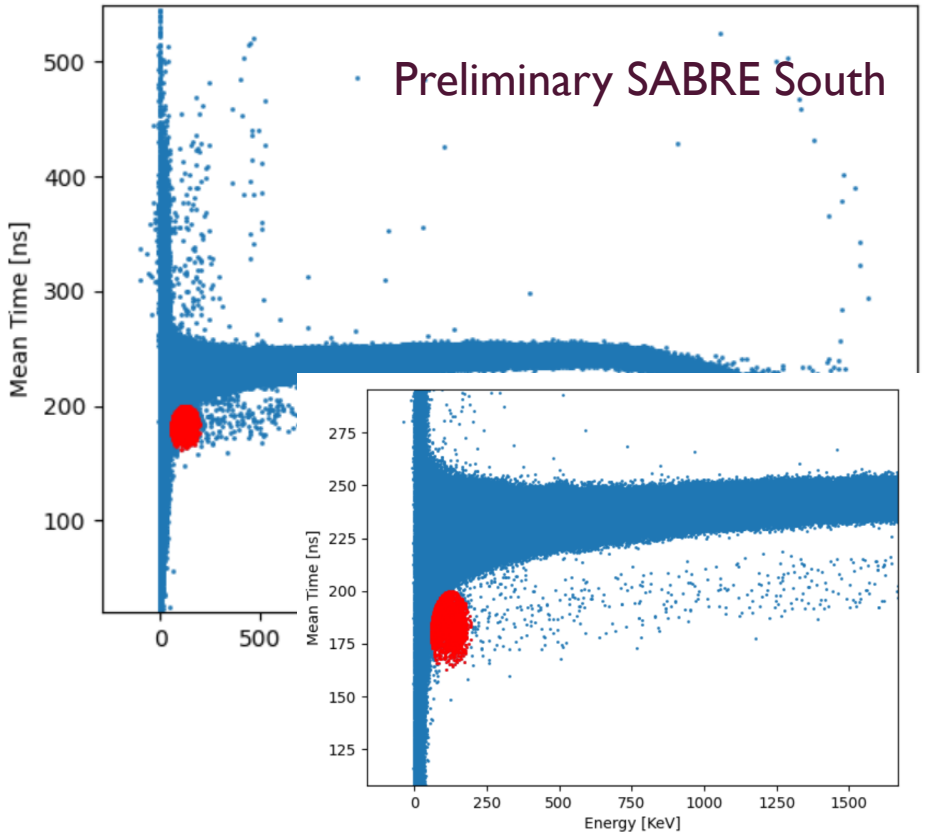
Data set	Duration (days)
Low Gain	~ 13
High Gain	~ 60

NaI-033: 5.9 ± 0.6 μBq/kg [1]

[1] arxiv: 2012.02610

UNKNOWN REGION – 'PROTRUSION'

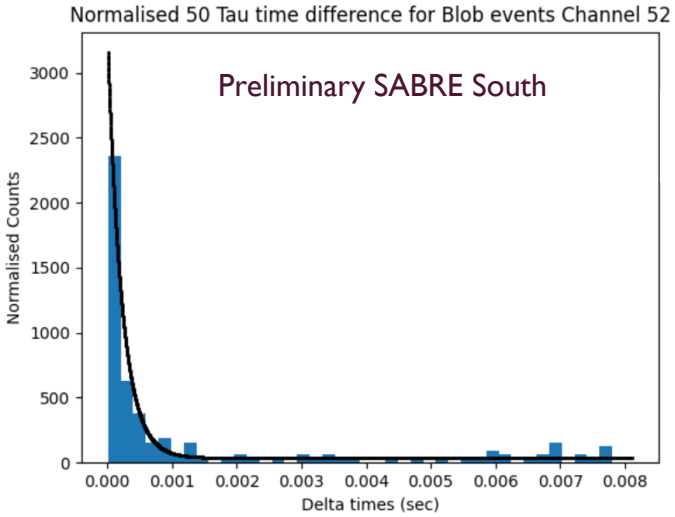
- Unknown excess of counts at low energy
  - α-like mean times
- Present in High and Low Gain data

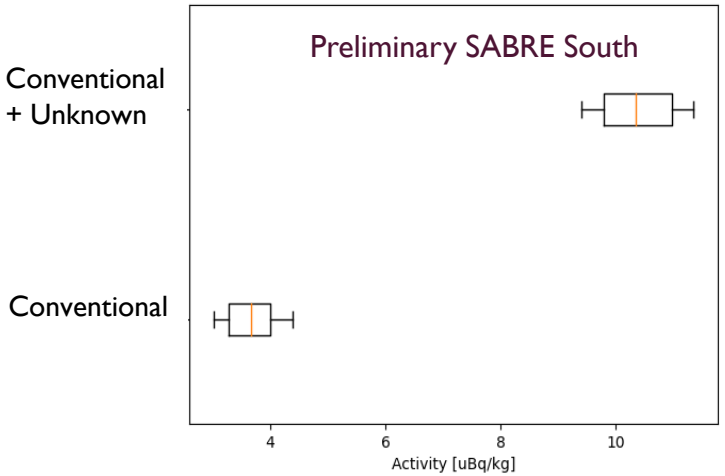


ANALYSIS ON UNKNOWN REGION

- Repeat likelihood fit on unknown region
- Can calculate $t_{1/2}$ that fits to this:
  - Unknown region: 153 ± 25 μs (± 1σ)
  - Conventional analysis: 122 ± 40 μs (± 1σ)
- Unknown region + standard: 10.4 ± 0.9 μBq/kg
  - Compared to 3.7 ± 0.7 μBq/kg
- Could be surface α
  - Working toward determining if this needs to be included in α

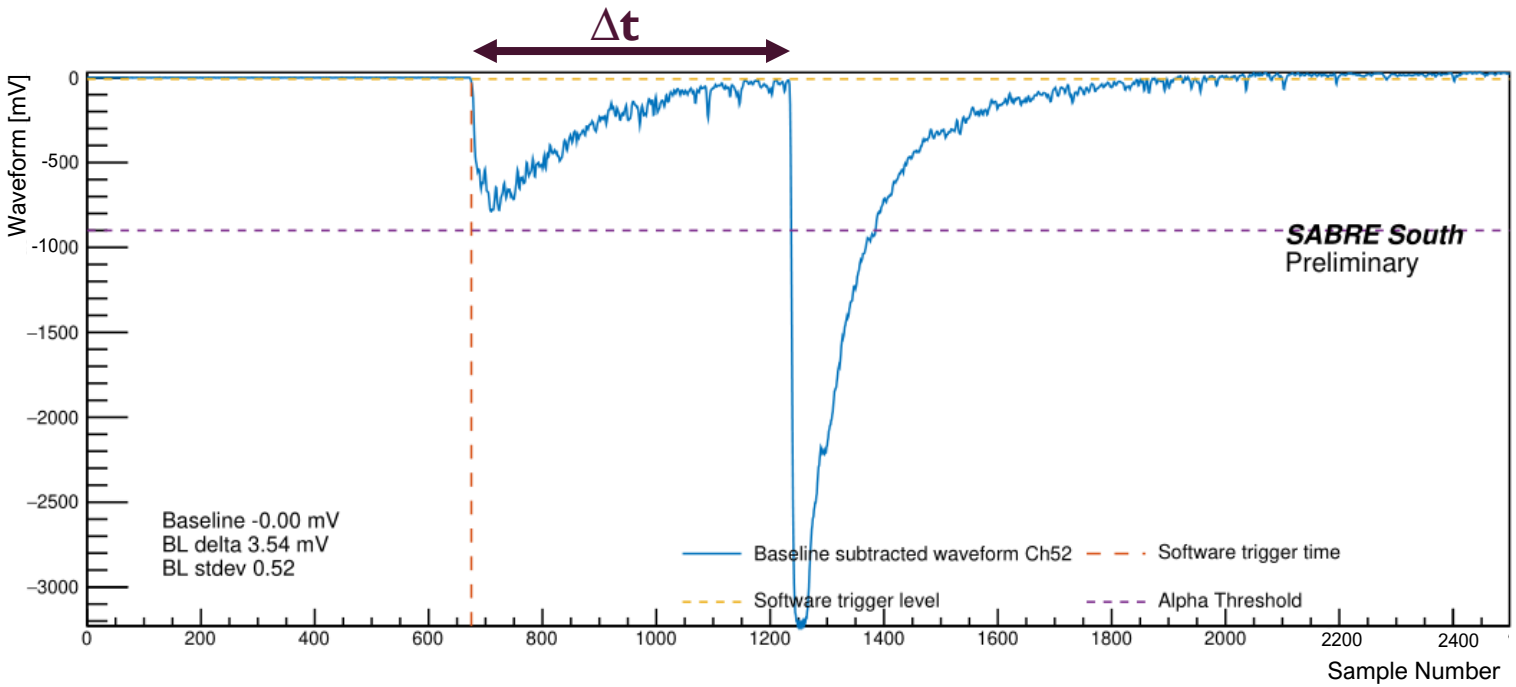
High gain





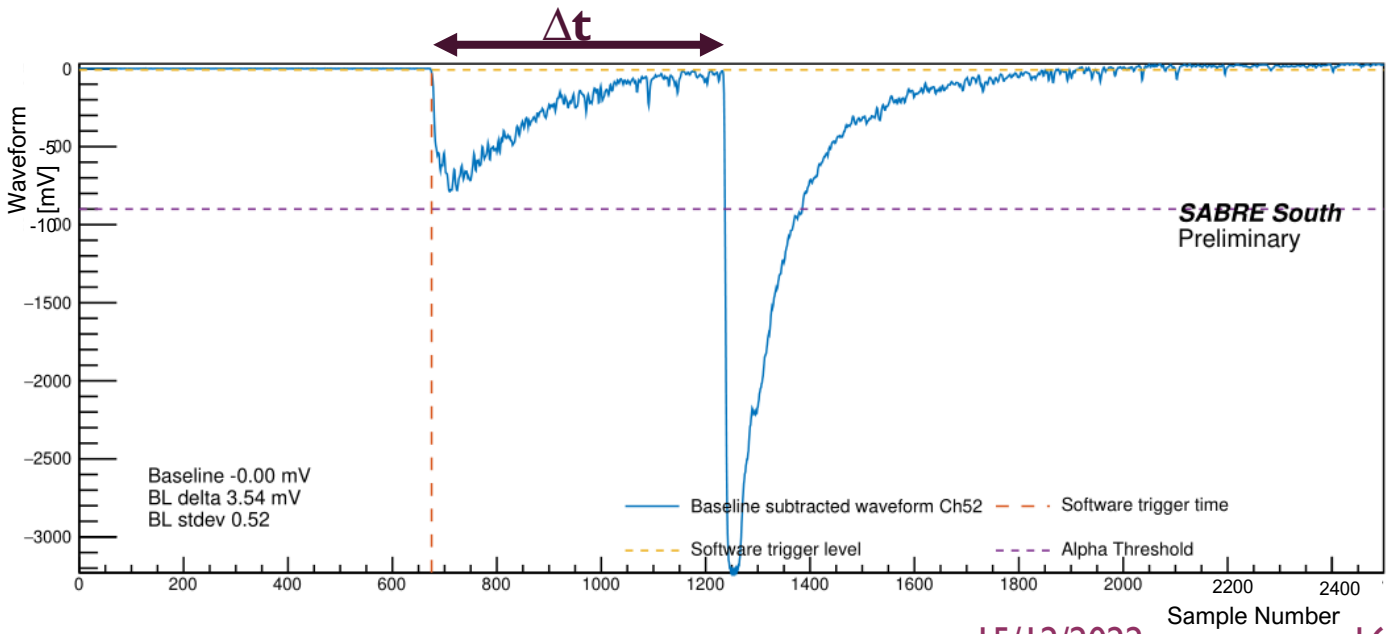
FAST BIPO

- Looking for β followed by an α with $t_{1/2}$ = 300 ns
  - Digitiser recording window = 5 μs
  - Look in one trigger



FAST BIPO

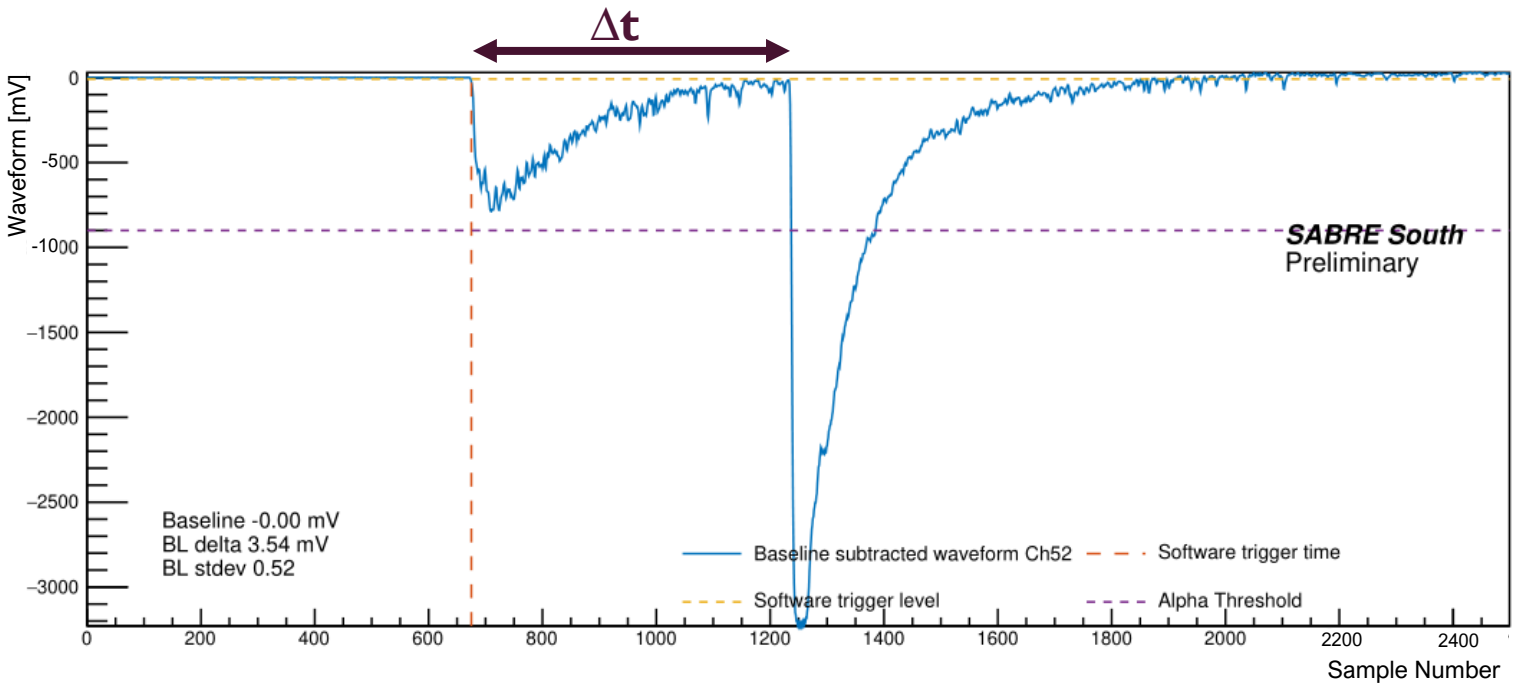
- Set Alpha trigger threshold
  - Set a minimum Δt
  - Requires some experimentation
- Activity by counting number of BiPo events and assuming 100% efficiency
- Preliminary High Gain – 1.4 ± 0.2 μBq/kg
- Preliminary Low Gain – 1.2 ± 0.4 μBq/kg
- NaI-033: 1.6 ± 0.2 μBq/kg [1]



[1] arxiv: 2012.02610

FAST BIPO

- Current waveform processing algorithm may miss events is the β peak is larger than the α threshold
- Δt currently requires experimentation
- Working toward developing an algorithm to detect two energy deposits more accurately
- Once we have good number, we can do a similar analysis to slow BiPo

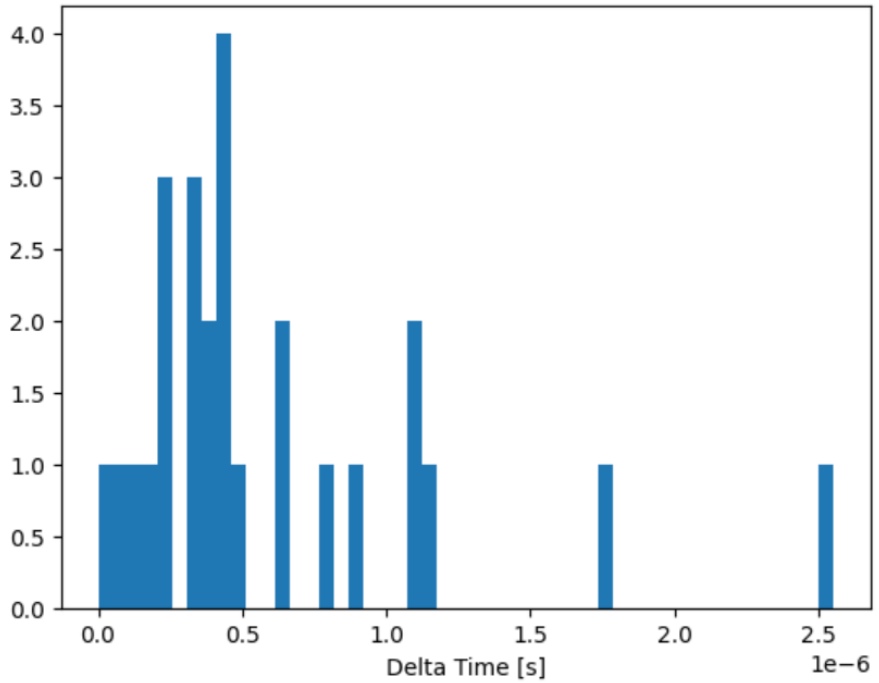


CONCLUSION

- Developed a method to identify and analyse BiPo in the ^{238}U decay
- Need to determine if unknown region protrusion should be included in α
  - Could have implications for crystal contamination
- Developed the basic analysis and method to identify BiPo in the ^{232}Th decay
  - Needs algorithm improvements
- So far results are compatible with NaI-033.

FAST BIPO

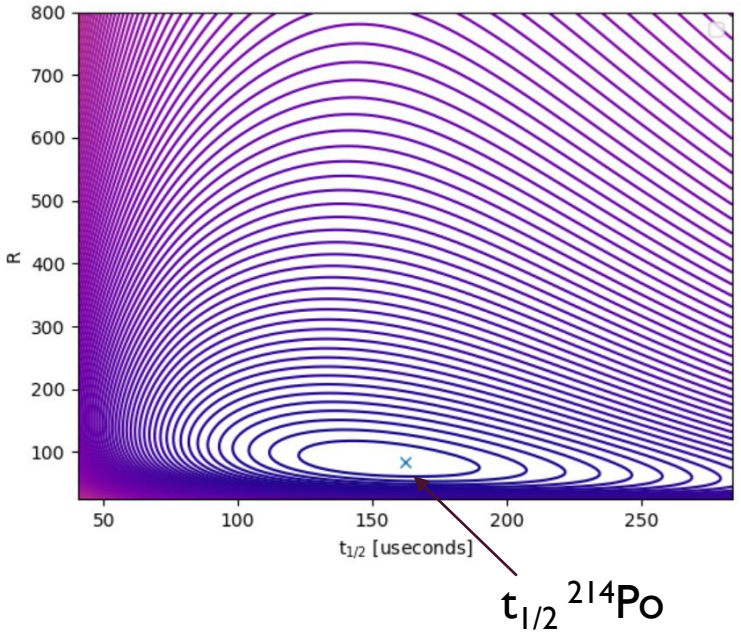
- Set Alpha trigger threshold
  - Requires some experimentation
- Identified 26 events

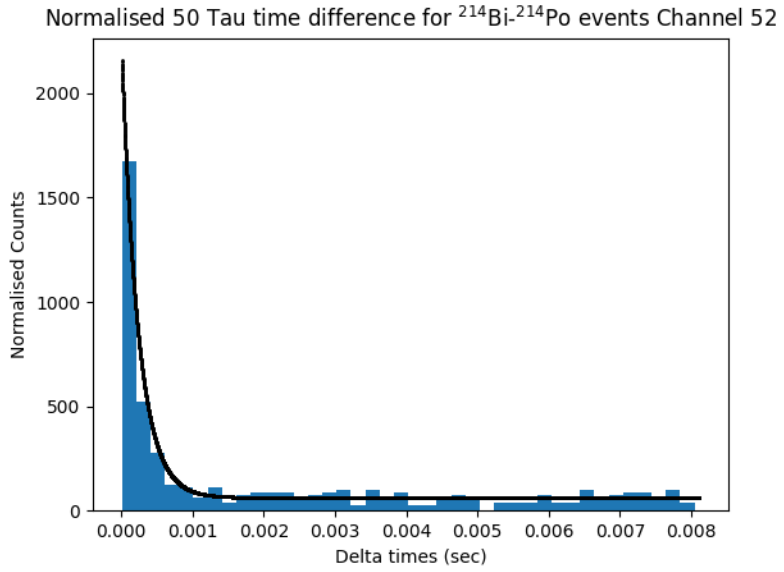


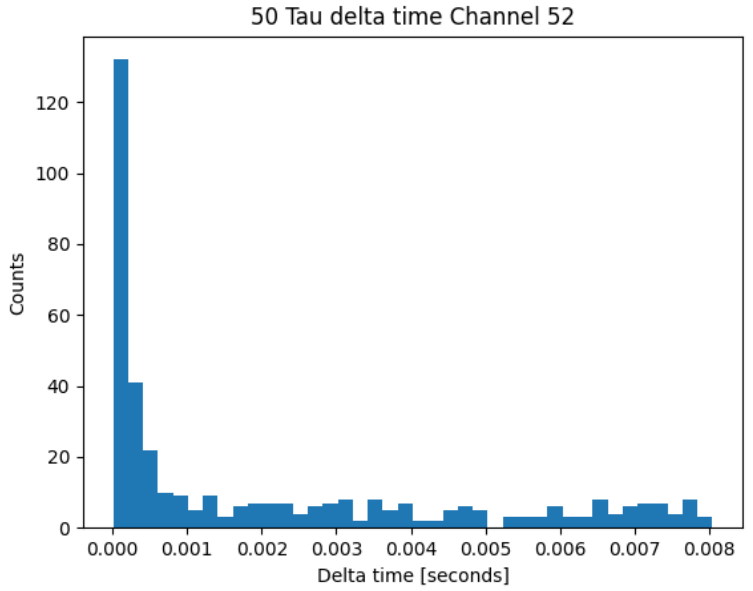
BLOB INCLUDED ANALYSIS

THE FOLLOWING ΔT DISTRIBUTION IS FOR THE BLOB INCLUDED IN THE OVERALL ANALYSIS.

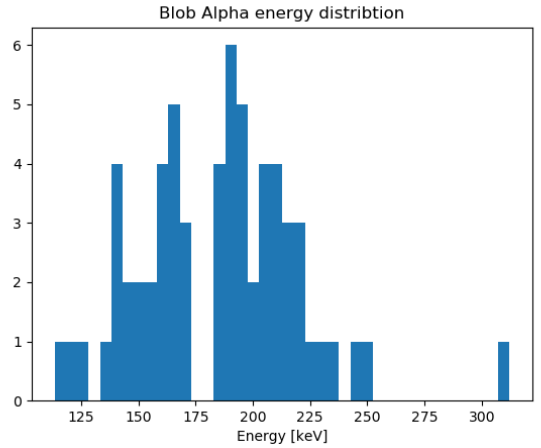
Preliminary SABRE South

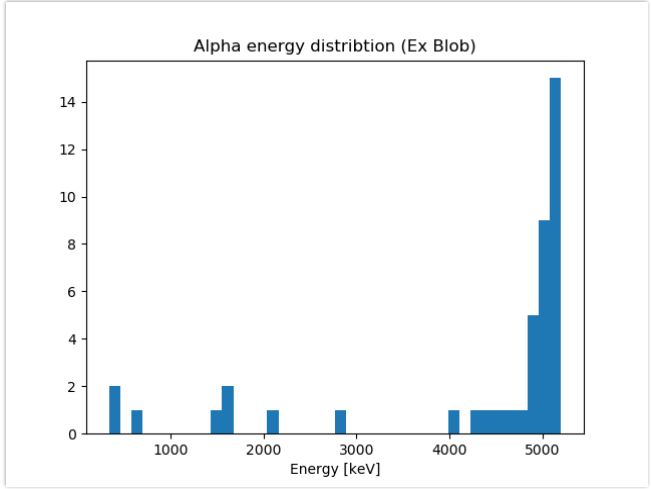


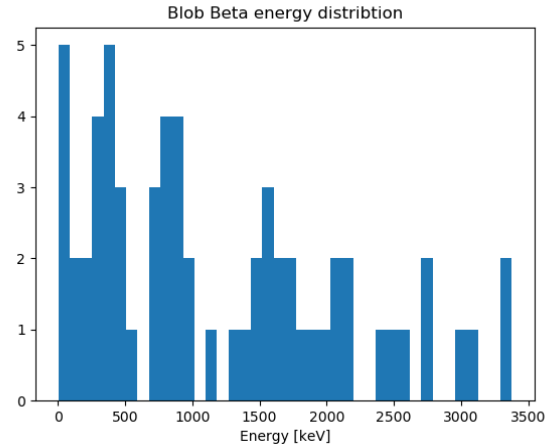


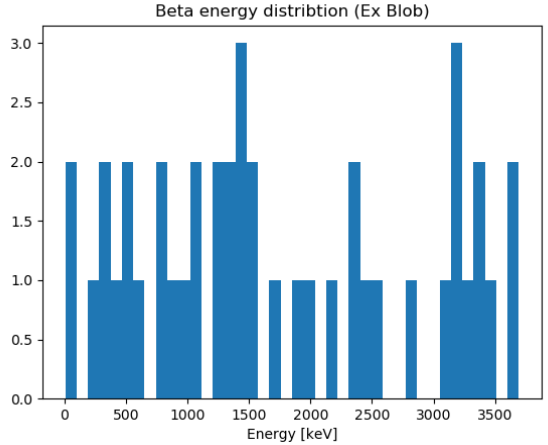


BLOB INCLUDED ANALYSIS









NON-BLOB

- $I = \int_0^{tmax} N(1 + Re^{\lambda t})$
- BiPo Percentage = $1\text{-}Nt_{max}$