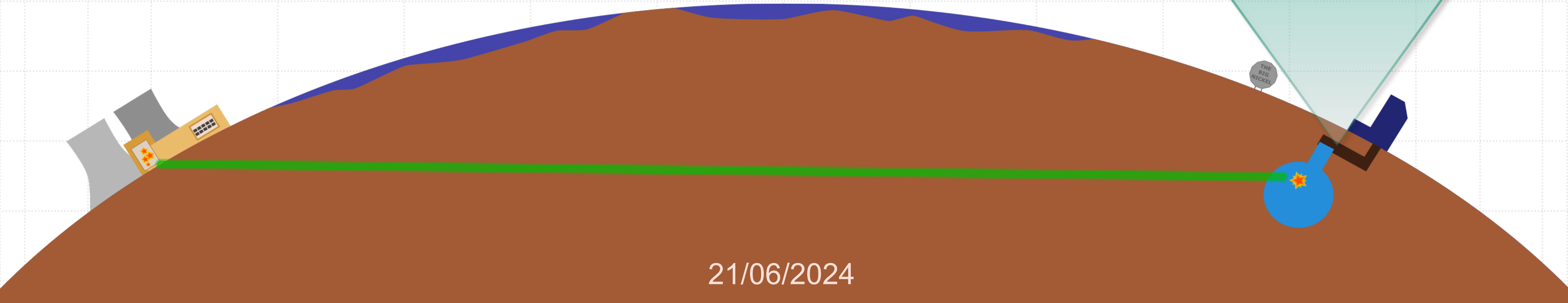
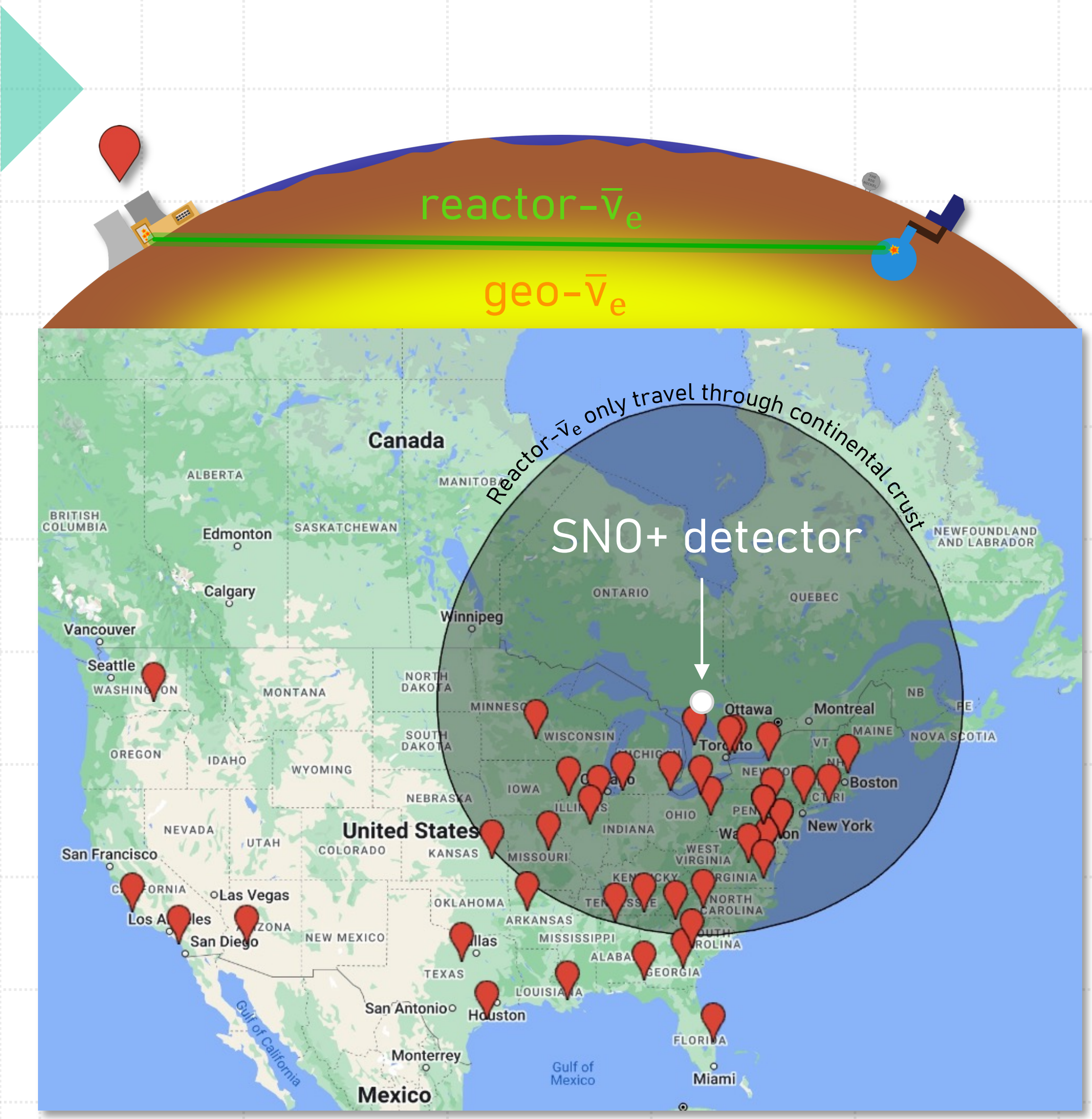
Event-by-Event (α, n) and IBD Discrimination at SNO+

James Page

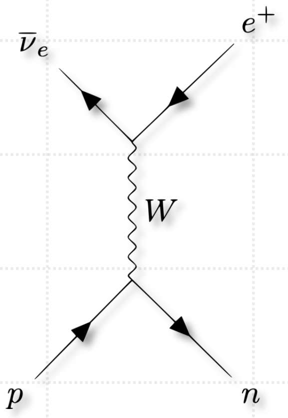


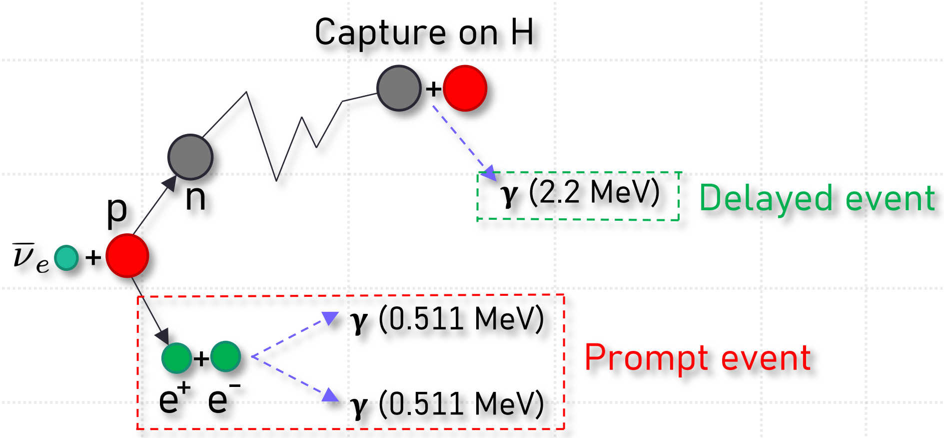
21/06/2024

IBD from $\bar{\nu}_e$



- Inverse Beta Decay (IBD) produced by $\bar{\nu}_e$:





- Two primary sources of $\bar{\nu}_e$ on Earth are:

1: Reactor-ν

- Long baseline neutrino oscillation.
- Measurement of Δm^2_{21}.

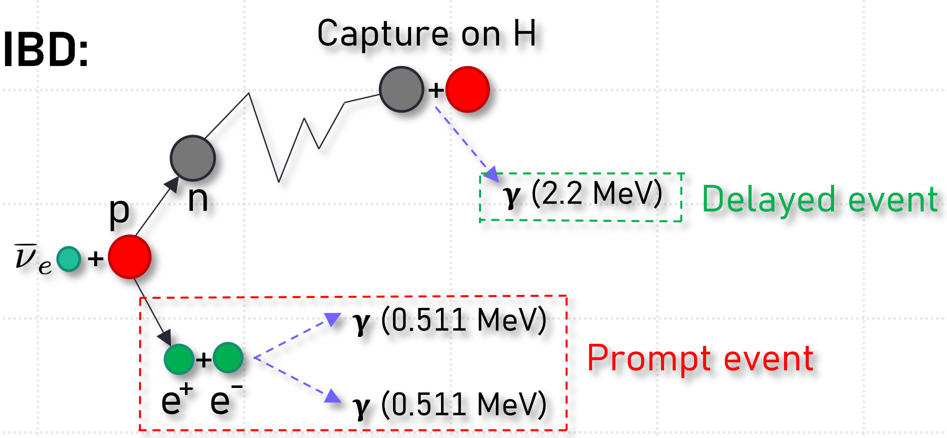
2: Geo-ν

- Produced by naturally radioactive elements in the Earth (crust + mantle).
- Study of inner-Earth models!

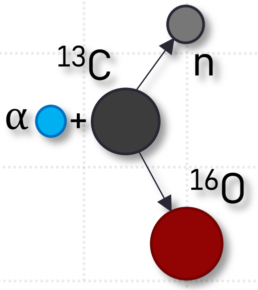
IBD vs (α, n) Events

- IBD prompt-delayed coincidence eliminates almost all backgrounds (τ_n ~ 200μs).
- Primary correlated background is $^{13}C(\alpha, n)^{16}O$:
  - Triggered by α particles from ^{210}Po decays capturing on ^{13}C inside the detector.
  - Mimics IBD signature: prompt + delayed n-capture.

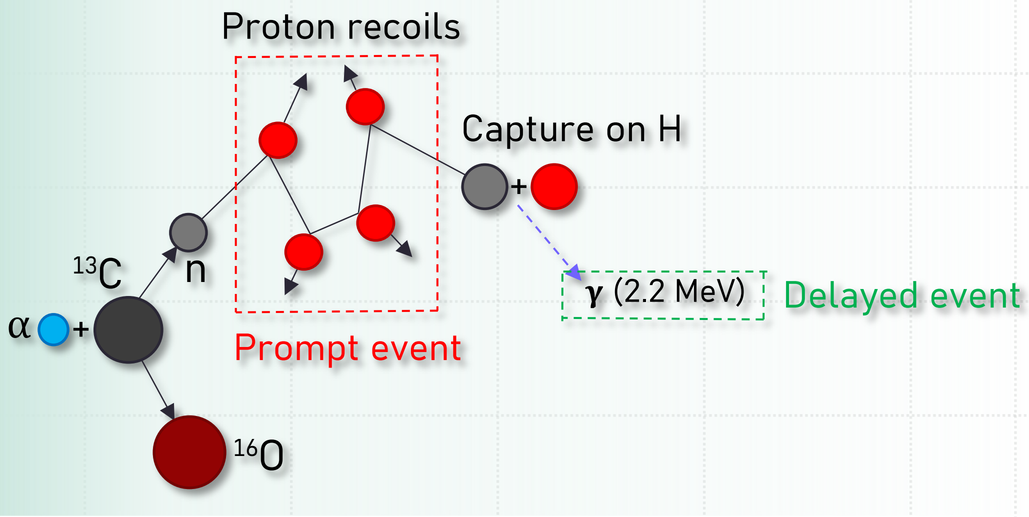
IBD:



(α, n):

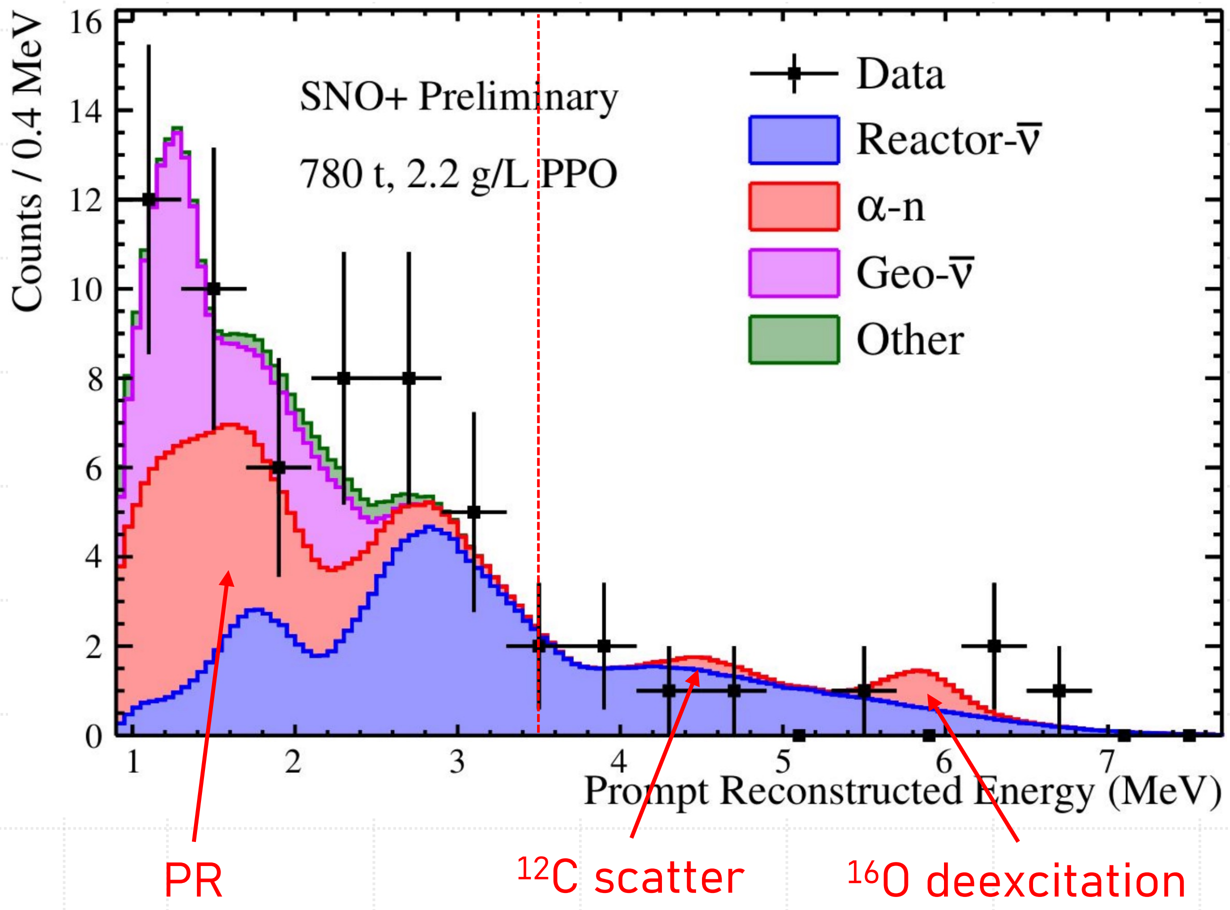


	$^{13}C(\alpha\text{-}n)^{16}O$ prompt events
GS ^{16}O	**Proton recoil (PR)**
	^{12}C scattering
ES ^{16}O	^{16}O deexcitation



IBD vs (α, n) Events

Full-fill oscillation analysis, fit prompt energy spectra:



- PR are the largest background.
- Large uncertainties in (α, n) cross-sections.

Geo-ν and PR normalizations are highly correlated: ρ ~ -0.57

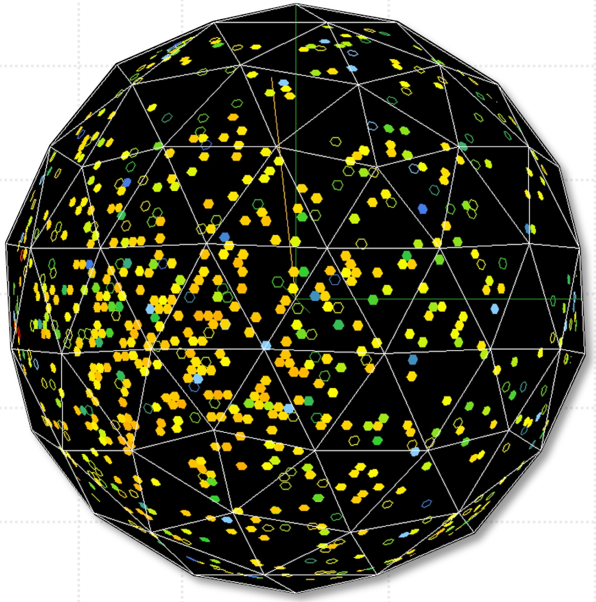
Geo-ν flux measurement can be greatly improved by reducing the PR background!

Can also improve reactor-ν oscillation analysis!

Only looking at events below 3.5 MeV from now on ---- (0.9 to 3.5).

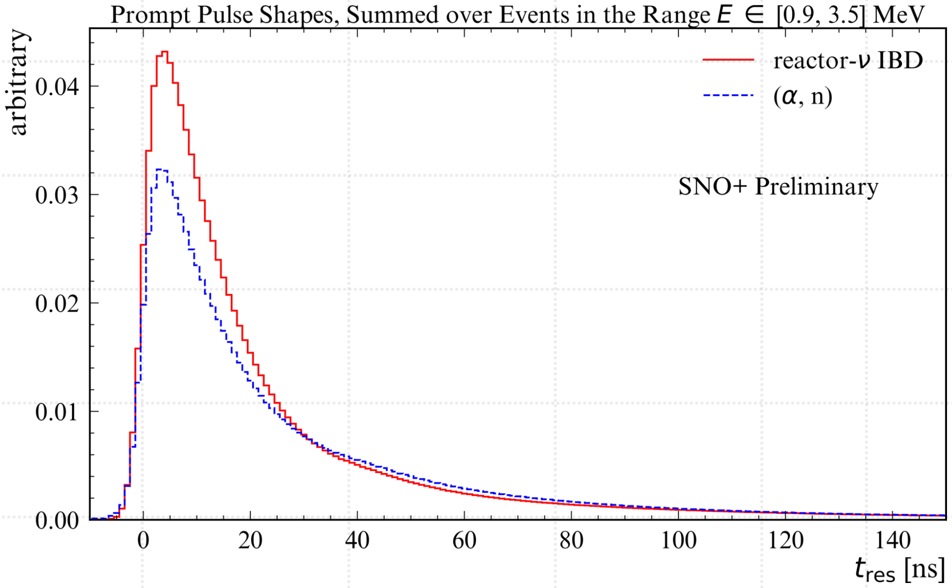
Pulse Shapes

- Liquid scintillator provides almost no directionality information.
- Only use number of PMT hits (N_{hit}) and relative timing/position of these:



Reconstruction:
- $N_{hit} \propto E$ (roughly).
- Event t and $\vec{r}$ are fitted.

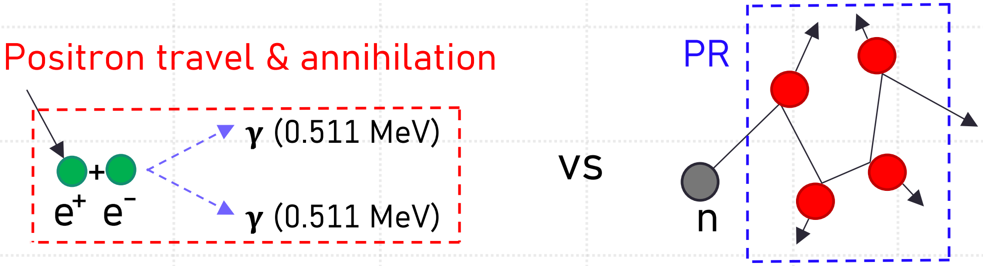
Pulse shape (time residuals):
- $t_{res} = t_{PMT\ hit} - t - t_{TOF}$



- PR occur over a longer period.

  ➡ **Longer tail in the pulse shape → can classify!**

- Scintillation response of to protons is also different.



Scintillator Timing

- Classifier based on MC simulations.
- Simulated pulse shapes sensitive to scintillator emission time for each particle:

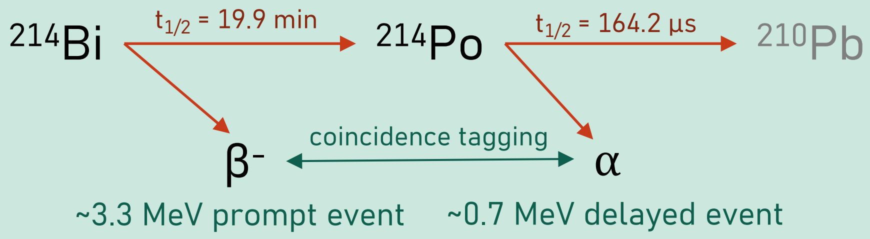
$$f(t) = \sum_{i=1}^{n} N_i \frac{e^{-t/\tau_i} - e^{-t/\tau_{\text{rise}}}}{\tau_i - \tau_{\text{rise}}}$$

- N_i and τ_i are specific to each particle type $\rightarrow$ must be tuned:

β timing				
i	1	2	3	
τ_i	-5.0	-24.46	-399.0	
N_i	0.656	0.252	0.092	
p timing				
i	1	2	3	4
τ_i	-4.1	-21.0	-84.0	-197.0
N_i	0.523	0.656	0.252	0.092

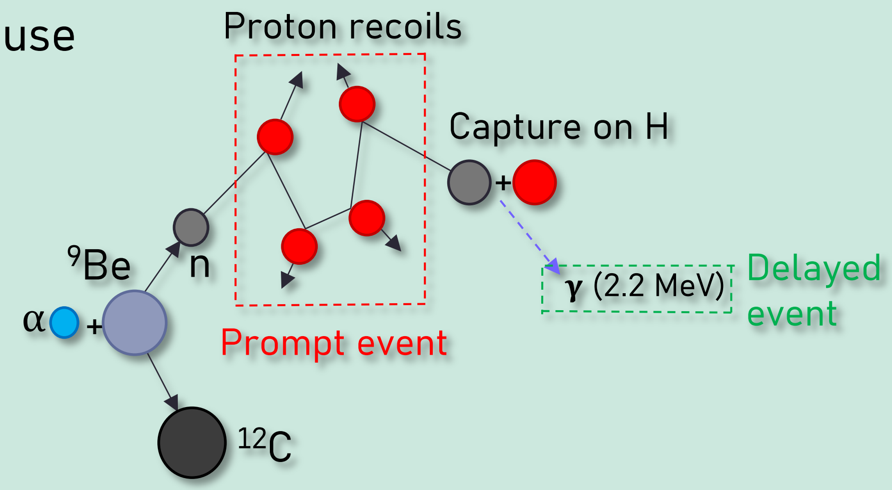
β timing

Use tagged in-situ Bi-Po events:



proton timing

Attempting to use AmBe source:



^{9}Be(α,n)^{12}C (PR)

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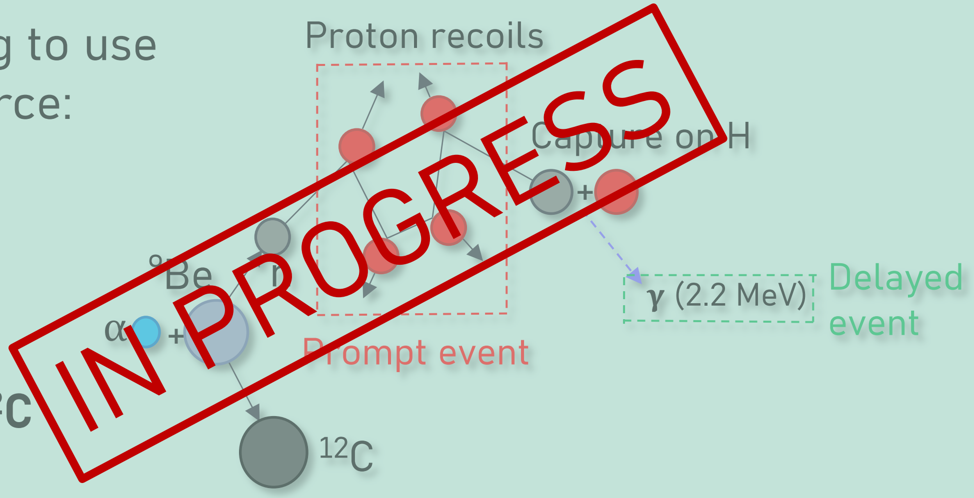
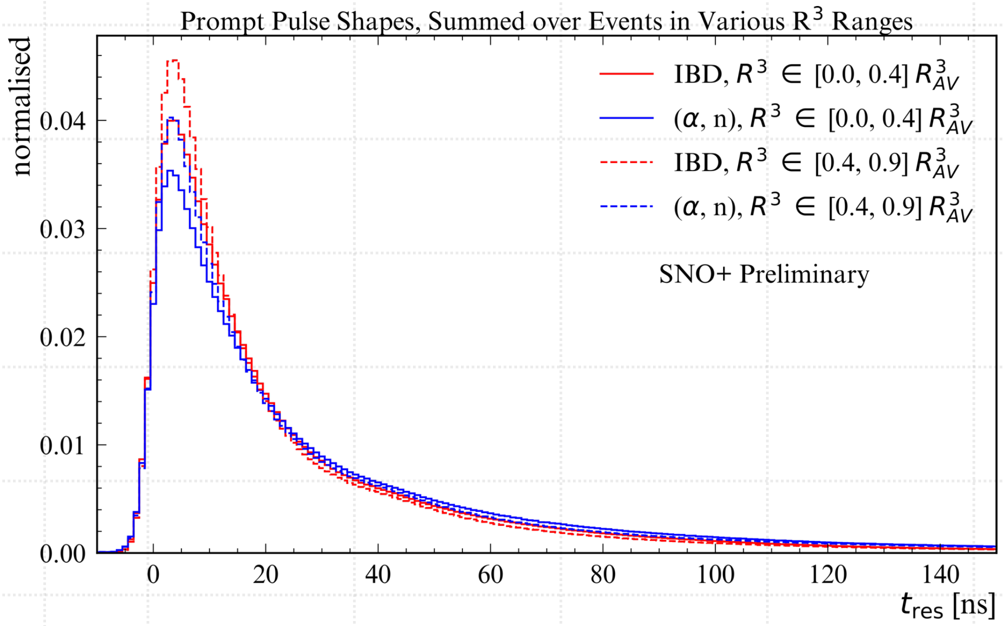


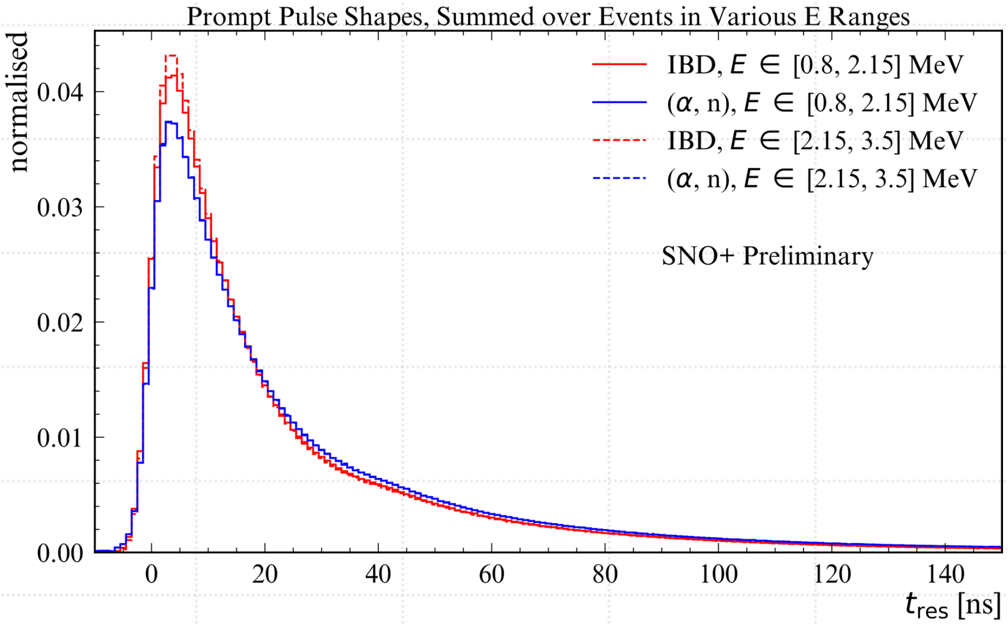
^{9}Be(α,n)^{12}C (PR)

(plots show events sampled from uniform E and R^3 distributions)

Pulse Shape Correlations

Pulse shapes are **correlated** with the event's reconstructed energy **E** and radial position **R** non-trivially:



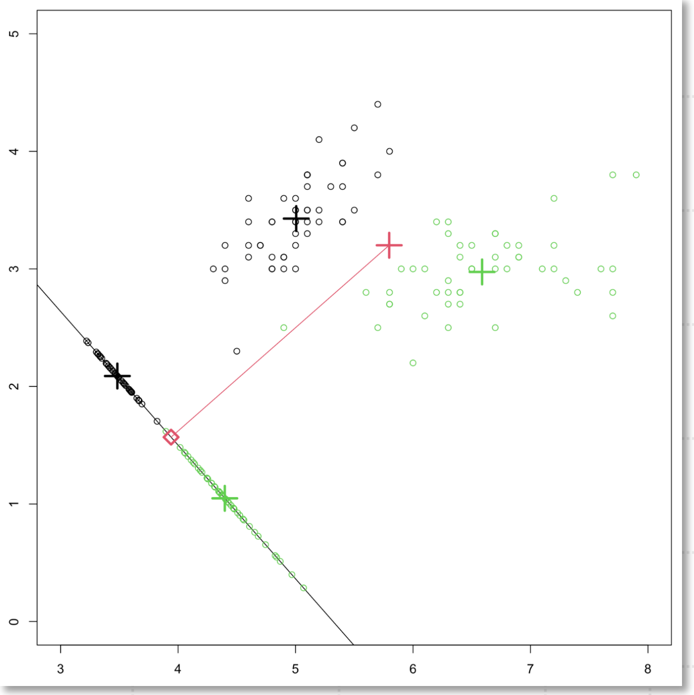


- A likelihood ratio based on averaged PDFs does not capture this:
  Treats each PMT hit as an independent measurement (Neyman-Pearson lemma) → not true.
- The choice of what energy spectrum to draw events from carries assumptions.

➡ Likelihood ratio not optimal. ➡ Use a **Fisher discriminant!**

Fisher Discriminant

- A type of linear discriminant analysis:
  - Reduce dimensionality of dataset: **projection to 1-D**.
  - Finds **projection vector** $\vec{\boldsymbol{a}}$ that best separates two classes of data.
- Details:
  - Maximise: $R = \frac{\vec{a}^T B \vec{a}}{\vec{a}^T W \vec{a}}$
    - “between-class covariance” (B)
    - “within-class covariance” (W)
  - Projection vector $\vec{a}$ that maximises R: $\vec{\boldsymbol{a}} = \boldsymbol{W}^{-1}(\vec{\boldsymbol{\mu}_S} - \vec{\boldsymbol{\mu}_B})$
  - Where: $\boldsymbol{W} = \frac{N_S}{N}\boldsymbol{\Sigma}_S + \frac{N_B}{N}\boldsymbol{\Sigma}_B$
- Classify each data-point $\vec{x}$ (event) with: $\mathbf{F} = \vec{\boldsymbol{a}} \cdot \vec{\boldsymbol{x}}$



https://rich-d-wilkinson.github.io/MATH3030/8.3-FLDA.html

Accounts for correlations!

But t_{res} is a 1-D distribution… ?

Classifier Tuning

- Construct a vector $\vec{x}$ for each event:

$$\vec{x} = (x_1, x_2, x_3, \dots, x_{n-1}, x_n)$$

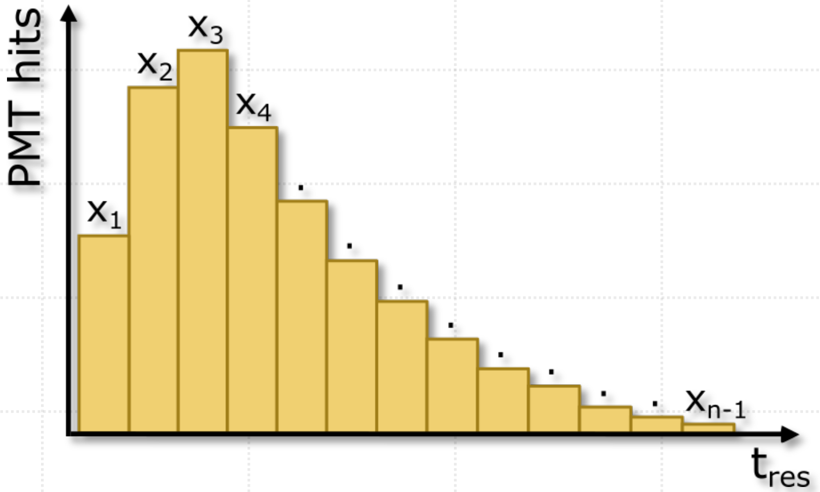
- Pulse shape and radial position included.
- Energy information already included from t_{res}:

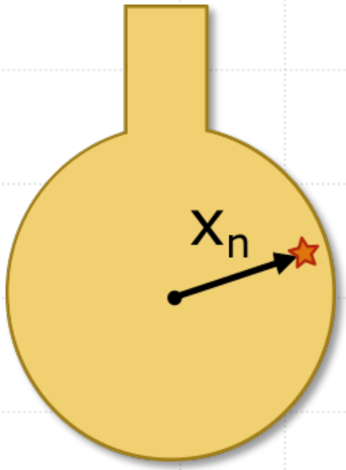
$$\sum_{i=1}^{n-1} x_i \approx N_{\text{hit}} \mathrel{\underset{\sim}{\propto}} E$$

- Compute $\vec{a}$ from MC simulated events:
  - Sampled from uniform E and R^3 distributions.
  - In the ranges expected to be used in analyses E ϵ [0.9, 3.5] MeV, $R^3 < 0.9\,R_{AV}^3$.
  - Assume $N_{IBD} = N_{(\alpha, n)}$ for now (see later).

➡ Classifier won't leverage different E-spectra (unknown a-priori in oscillation analysis)

Almost all t_{res} information + radial position





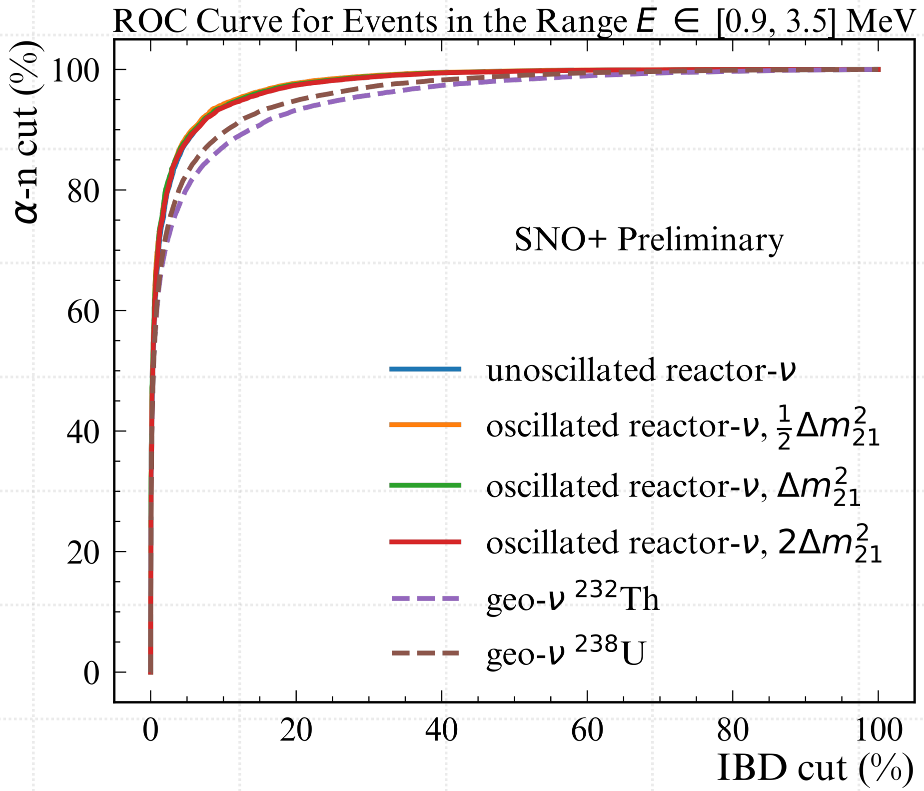
- t_{res} ϵ [-15, 150] ns → no improvement beyond this
- Bin width: Δt = 1ns → resolution limit, robust to larger binning.
- No improvement from adding E to $\vec{x}$, as expected.

Results

All events obey:
- $E \in [0.9, 3.5]$ MeV
- $R^3 < 0.9\ R_{AV}^3$

R_{AV} = radial position of acrylic vessel

- Simulate (α, n) and various IBD samples from expected "realistic" distributions.
- Apply tuned classifier to these:

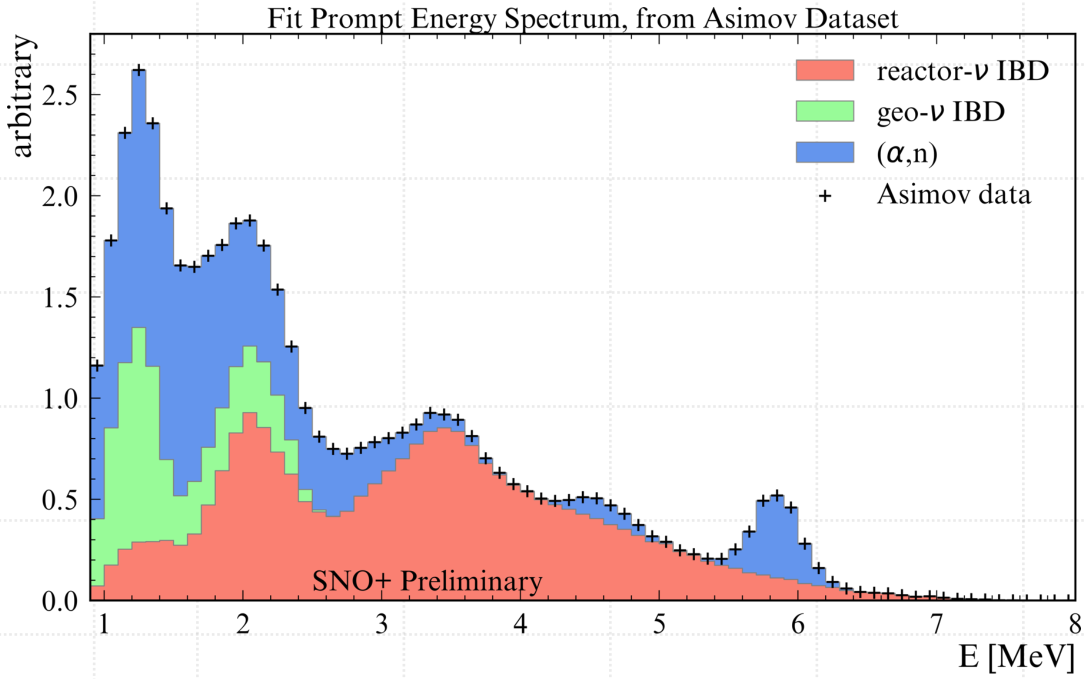


Can **cut 90% of (α, n)**, and only sacrifice:
- 6% reactor-ν IBDs.
- 11% geo-ν IBDs.

Performance is independent of oscillation parameters.

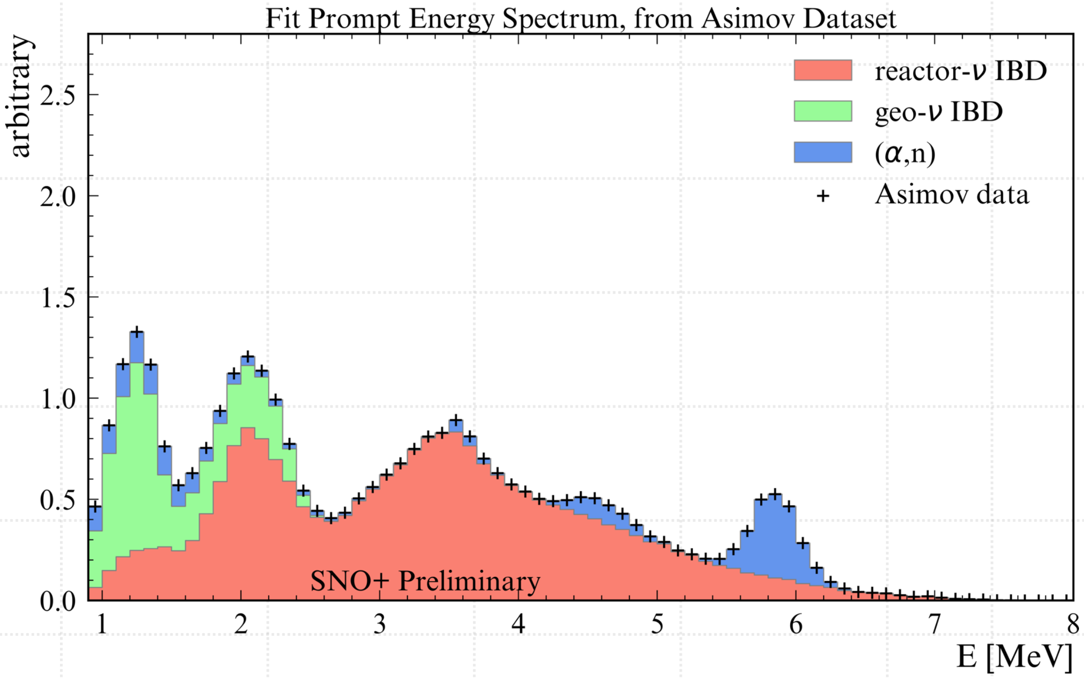
Results

Simulated impact on prompt energy spectrum:



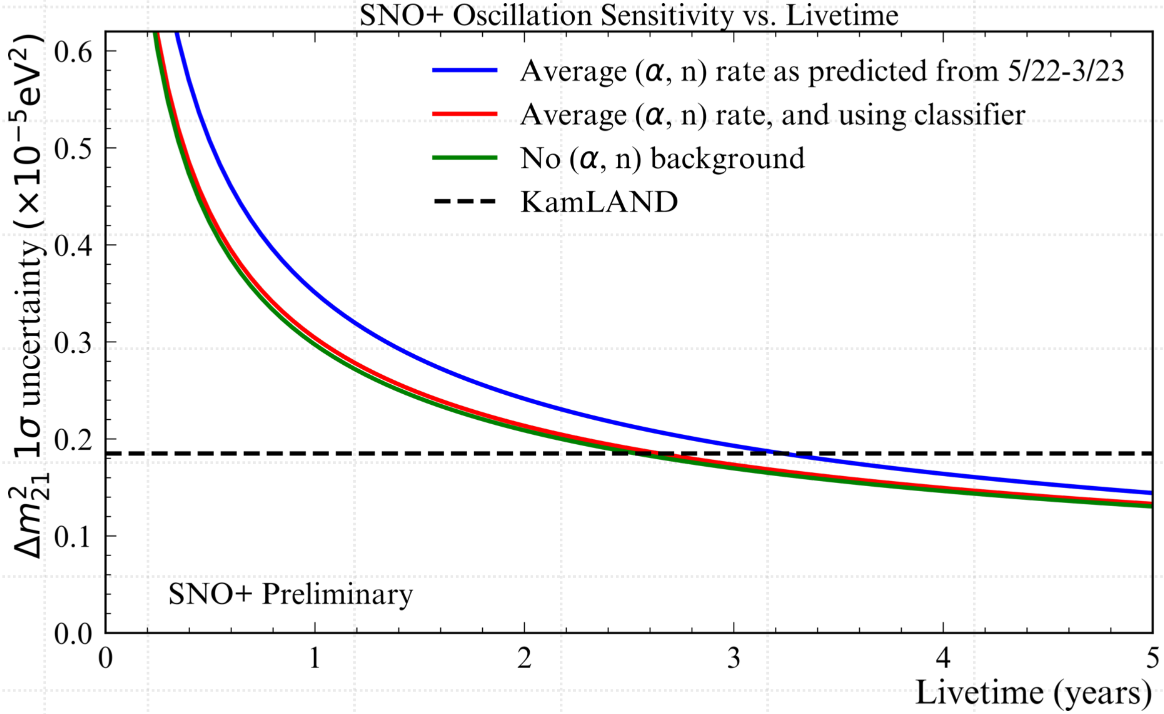
apply

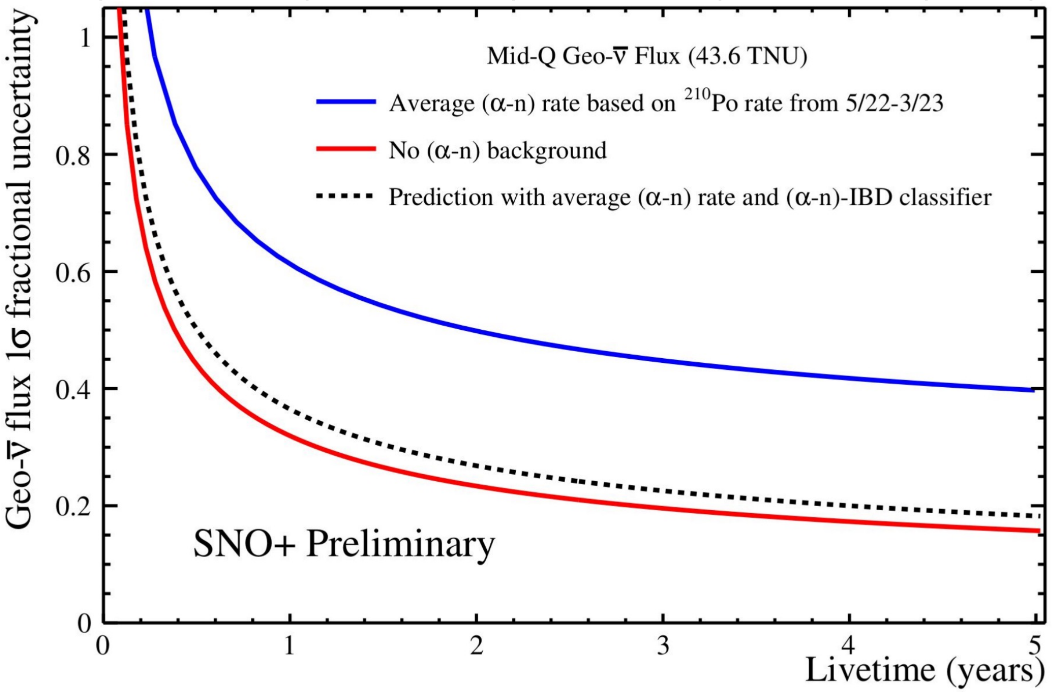
classifier



Results

Estimated sensitivity of SNO+ over time (Azimov data):





➡ Competitive measurement of Δm^2_{21} ~8 months sooner!

➡ Critical for geo-ν flux measurement!

Extra Notes and Potential Fine Tuning

Fine-Tuning

- **Classifier is for IBDs in general**, not tuned for either reactor-ν or geo-ν spectra.
- Could further slightly refine this classifier for to each case, via two methods:
  - Tune classifier on more "realistic" (α, n) and geo-ν/reactor-ν spectra → not tested yet.
  - Change ratio **r = N_S/N_B = $N_{IBD}/N_{(\alpha, n)}$**, recall:

$$\vec{a} = W^{-1}(\vec{\mu_S} - \vec{\mu_B}) \qquad W = \frac{N_S}{N}\Sigma_S + \frac{N_B}{N}\Sigma_B \Rightarrow W = \frac{r\Sigma_S + \Sigma_B}{1 + r}$$

- **So far set r=1** (equal weighting of signal and background)
- Can treat r as a hyperparameter, and tune it.

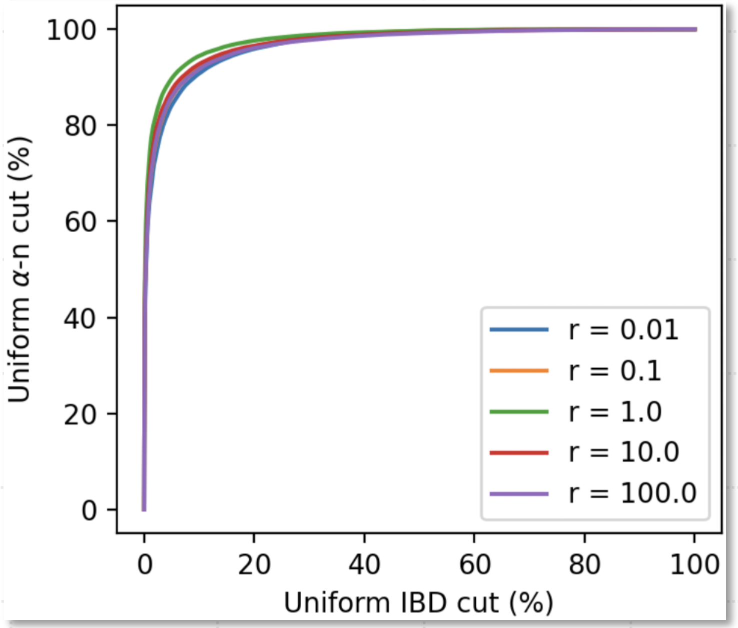
NOTE: Only small improvement potential, useful for higher statistics.

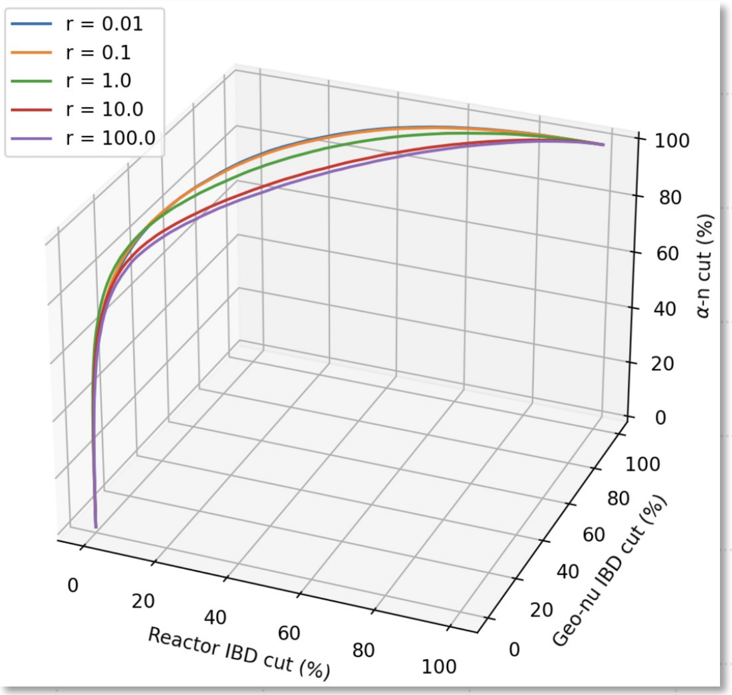
Fine-Tuning

- Classifier output is highly correlated with energy:

$$F = \vec{x} \cdot \vec{a} \quad \& \quad \sum_{i=1}^{n-1} x_i \approx N_{\text{hit}} \mathrel{\underset{\sim}{\propto}} E$$

- r is a handle on how much of this correlation is given to the signal vs background.
- Effectively **allows tuning of the energy response of the classifier**: favour geo-ν or rector-ν?





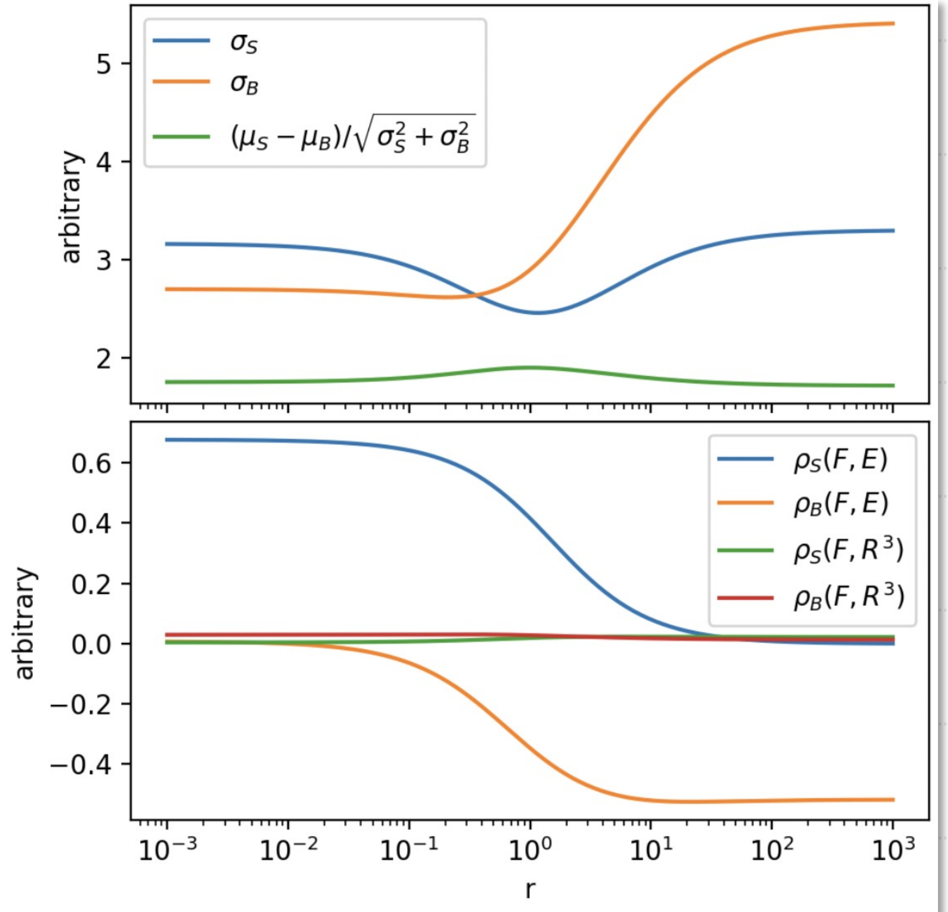
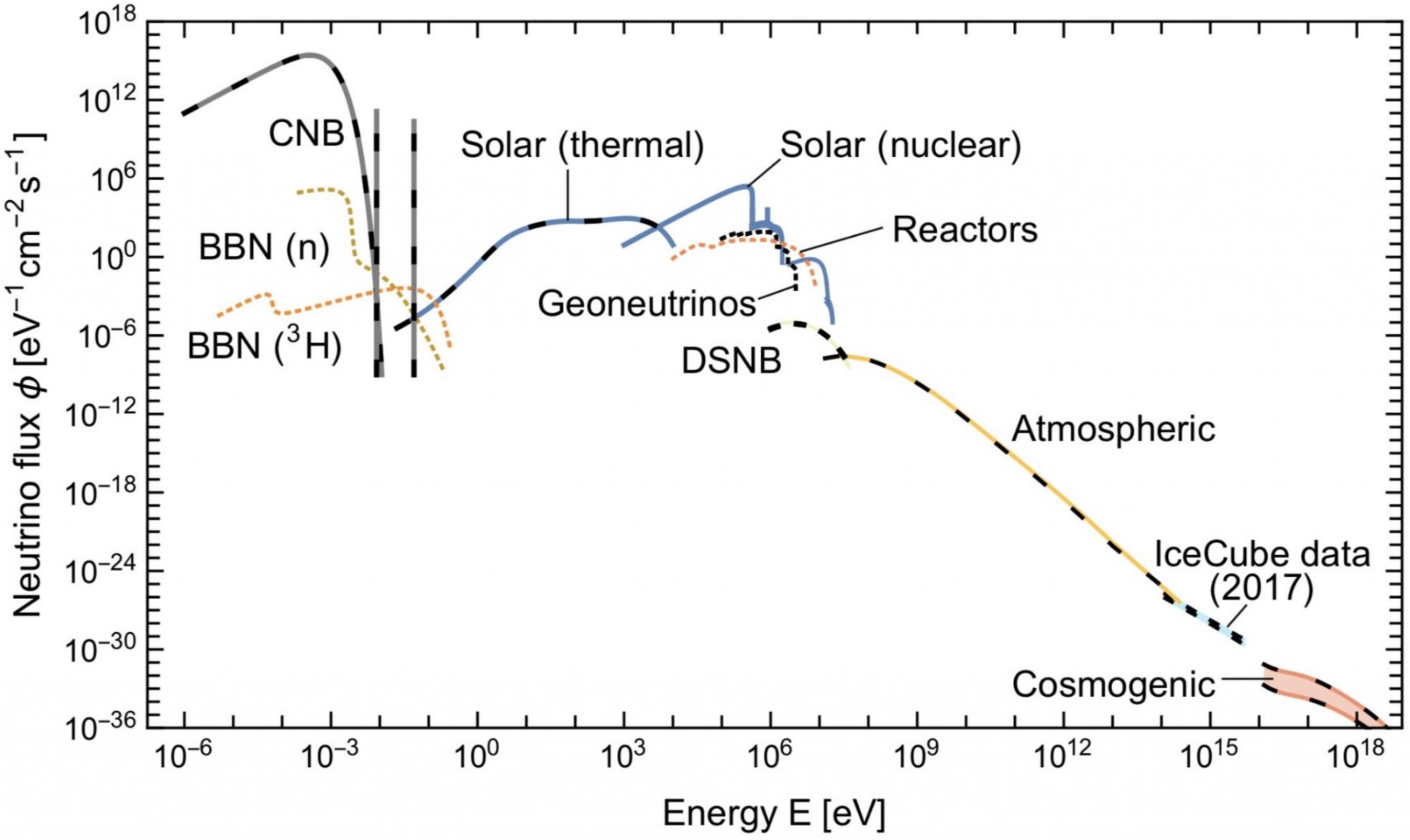


FIG. 6. Measured quantities of classified IBD signal and (α, n) background events, taken from uniform energy spectra, with classifiers trained using different values of $r = n_S/n_B$. Subscripts S and B indicate signal and background respectively, while F is the classifier output of an event, and $\rho(\cdot, \cdot)$ denotes the correlation between the two bracketed quantities.

Backup Slides

Grand Unified Neutrino Spectrum



Vitagliano, Edoardo, Irene Tamborra, and Georg Raffelt. "Grand unified neutrino spectrum at Earth: Sources and spectral components." *Reviews of Modern Physics* 92.4 (2020): 045006.