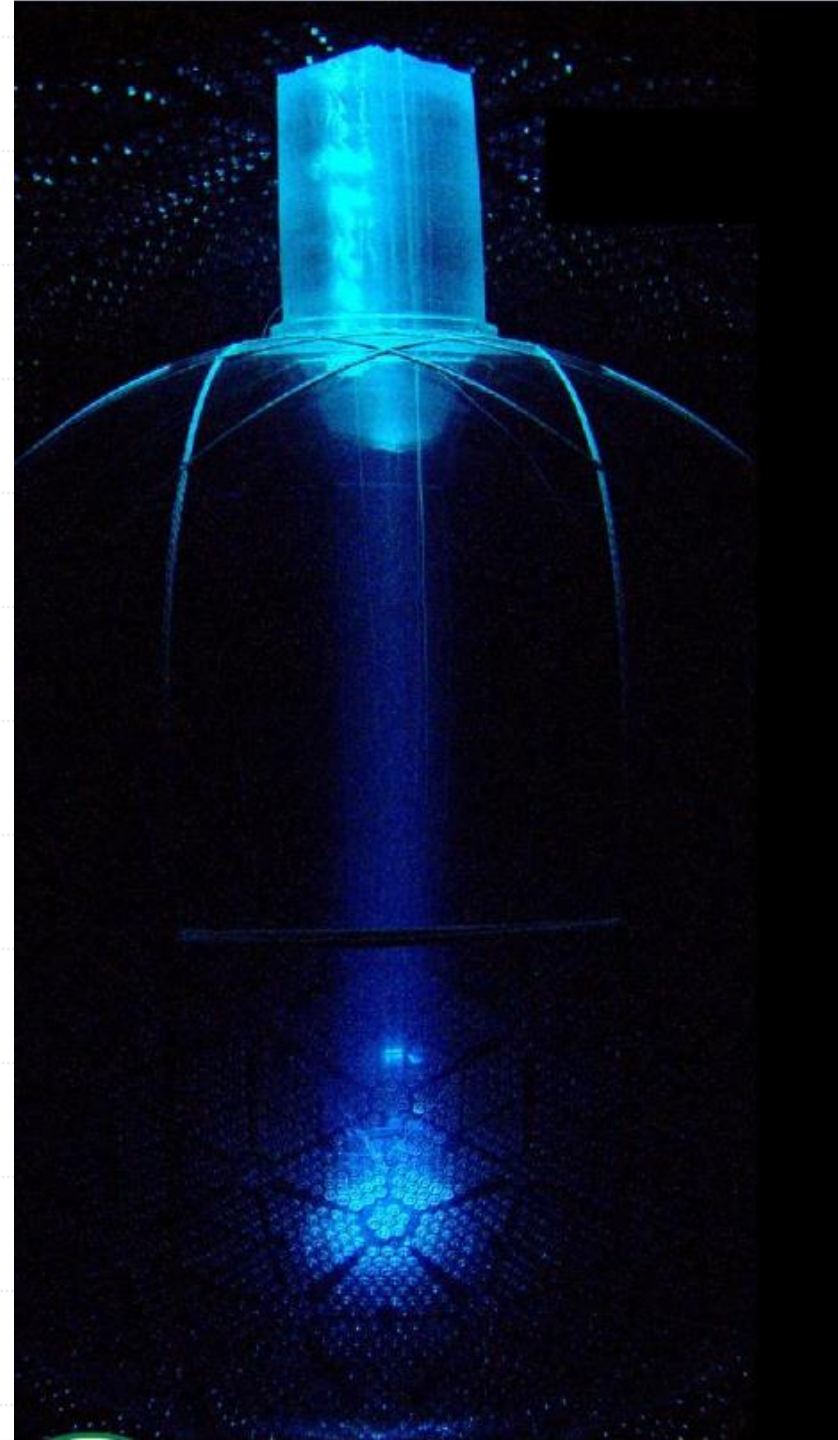


# The SNO+ Experiment

Detector, Results and Prospects

James Page

29/10/2025



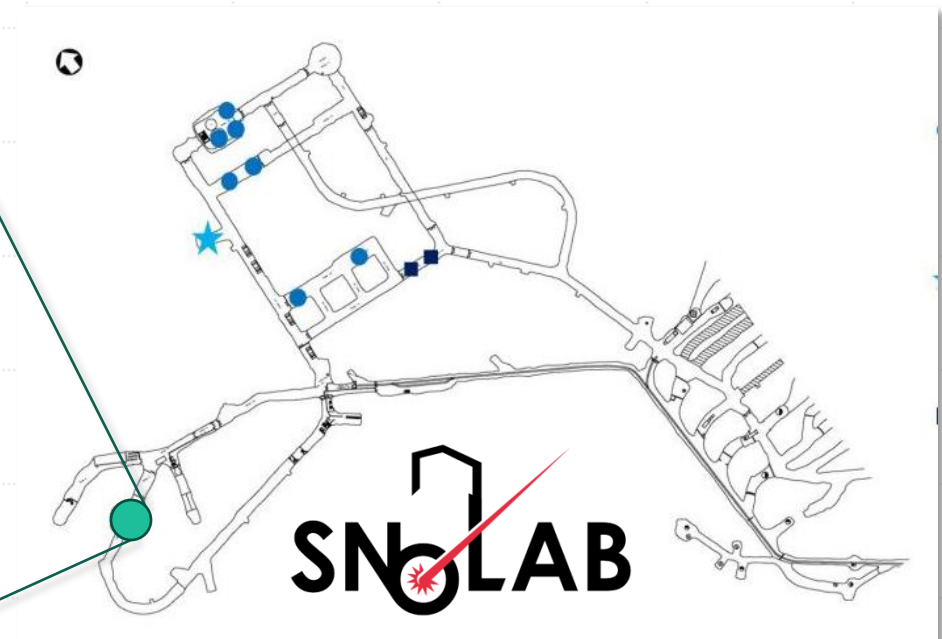
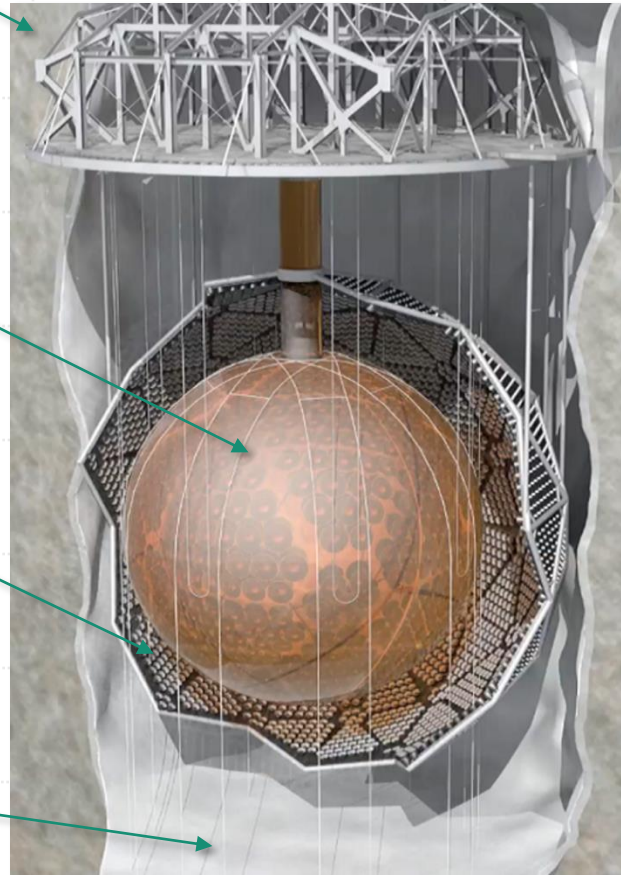
# The SNO+ Detector

2 km overburden

6 m radius acrylic vessel (AV) filled with liquid scintillator

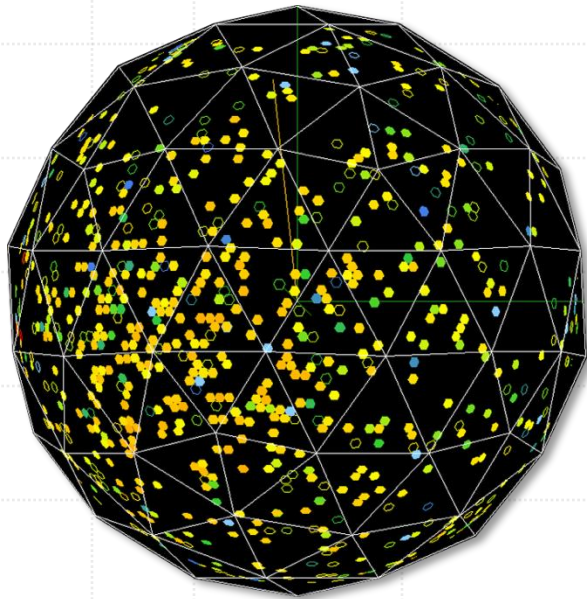
Over 9000 PMTs + outward looking PMTs

Surrounded by ultra-pure water



# Event Reconstruction

- Charged particles excite the liquid scintillator
- Liquid scintillator emits light isotropically
- Only use number of PMT hits ( $N_{\text{hit}}$ ) and relative timing/position of these:



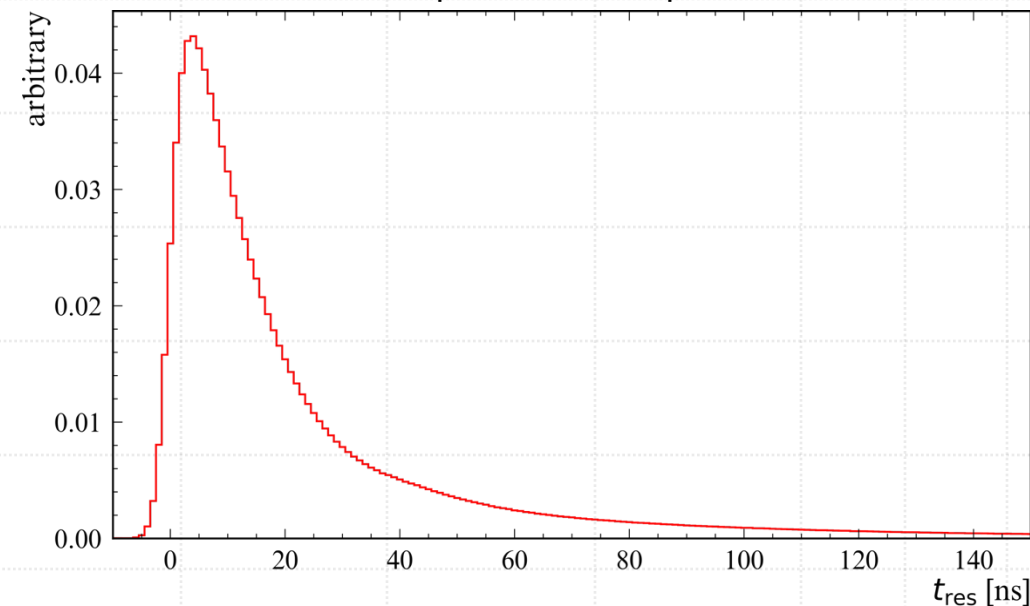
Reconstruction:

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

Pulse shape (time residual plot):

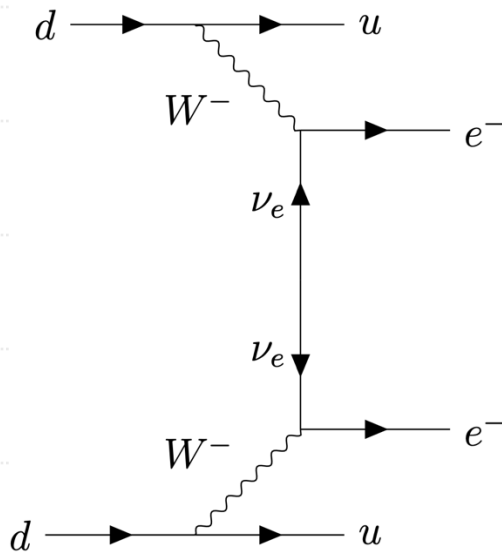
- $t_{\text{res}} = t_{\text{PMT hit}} - t - t_{\text{TOF}}(\vec{r})$

Example Pulse Shape PDF:



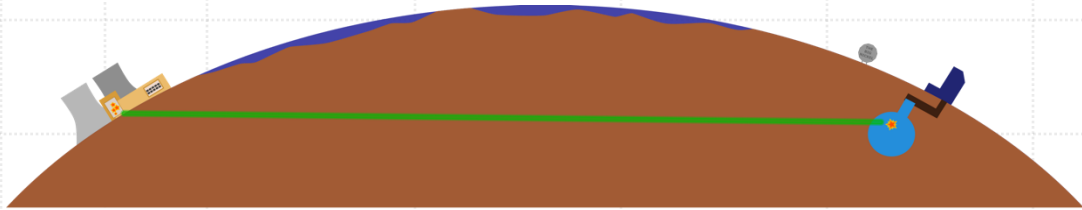
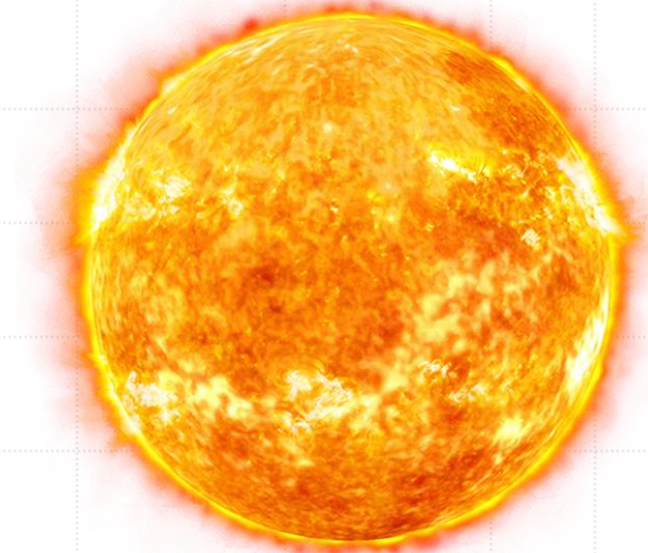
➔ Use these to identify physical processes!

# SNO+ Physics Goals



**Neutrinoless  
double-beta decay**

**Solar neutrinos**



**Reactor antineutrinos  
and geo-neutrinos**

supernova early warning, ...

# SNO+ Timeline

## Water Phase



905 t ultra-pure water

Detector calibration  
External background  
measurements



## "Partial-fill" Phase



Half replaced with liquid  
scintillator (COVID19  
pause)

Scintillator optics and  
backgrounds



## Scintillator Phase



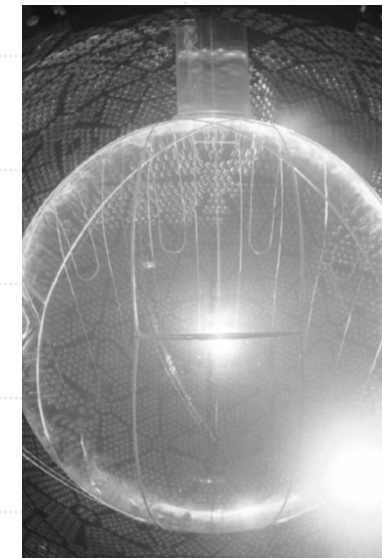
Completed loading of  
780 t liquid scintillator

LAB, 2.2g/L PPO (+ 2.2  
mg/L bis-MSB)

Initial → Enhanced



## Tellurium Phase



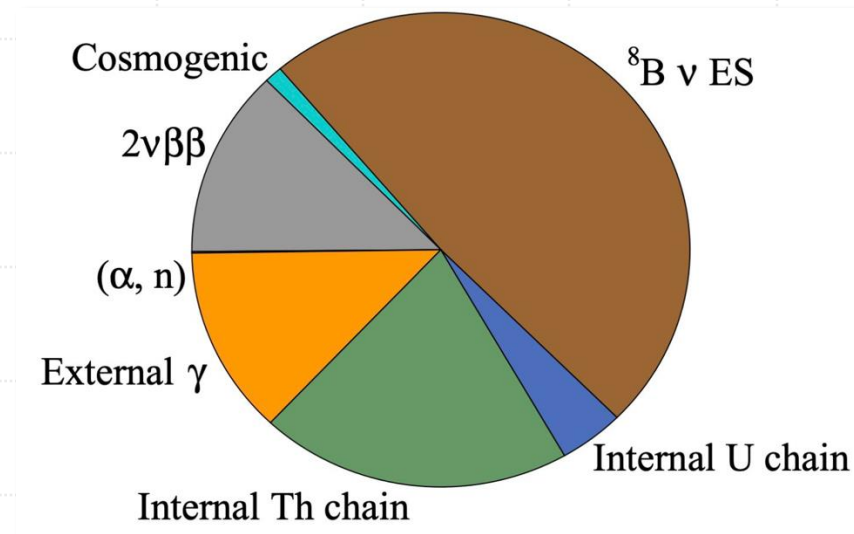
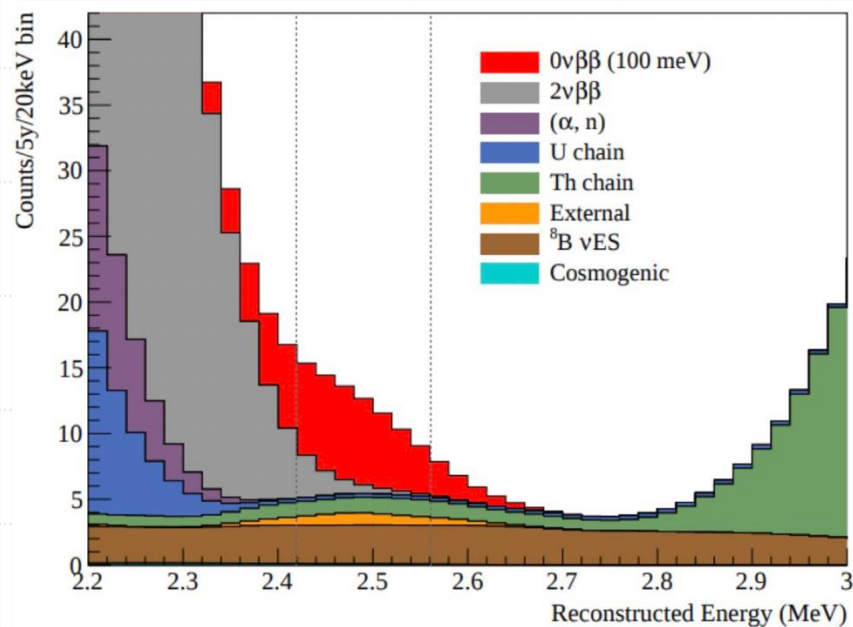
Progressive loading of  
Te

Start in 2026



# $0\nu\beta\beta$ Search

- Events in the region of interest (ROI) [2.42 – 2.56] MeV
- Expect 9.47 background events per year at nominal rates



- Expect sensitivity of  $T_{1/2} > 2 \cdot 10^{26}$  years, in 3 years of livetime, with 0.5% natural Te loading
- Potential for higher loading

# Physics Timeline

## Water Phase



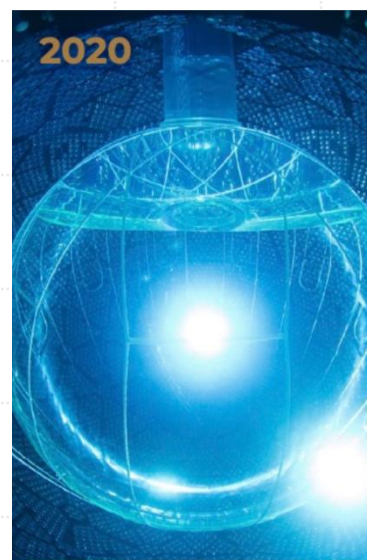
Solar neutrinos

Nucleon decay

First reactor  
antineutrinos detected  
in water



## "Partial-fill" Phase



Directionality in liquid  
scintillator

Reactor antineutrino  
oscillation



## Scintillator Phase

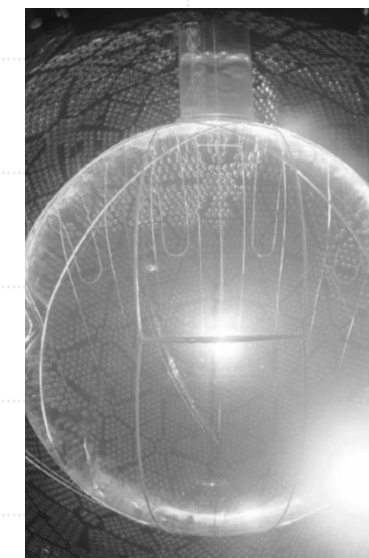


Reactor antineutrino  
oscillation and geo-neutrinos

First observation of solar  
neutrino interactions on  $^{13}\text{C}$



## Tellurium Phase



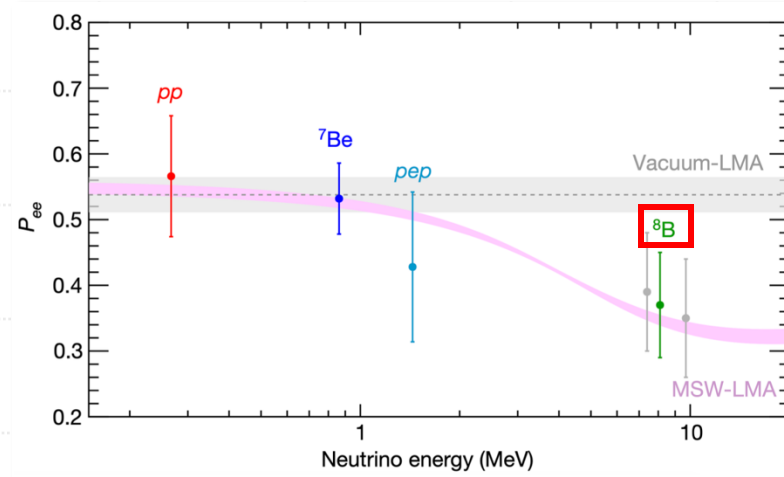
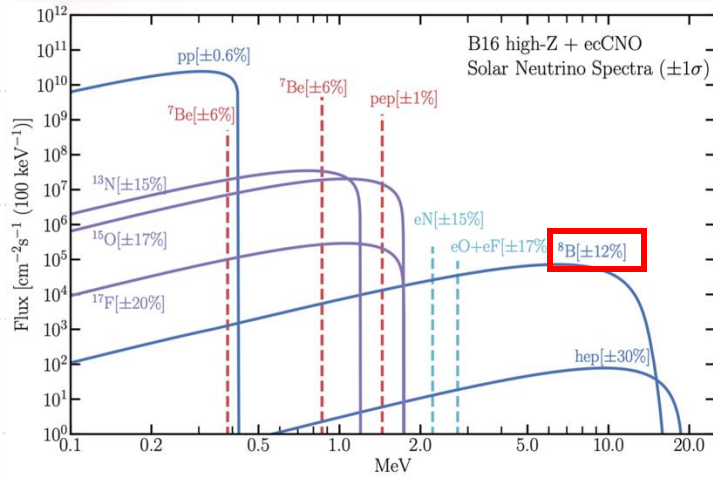
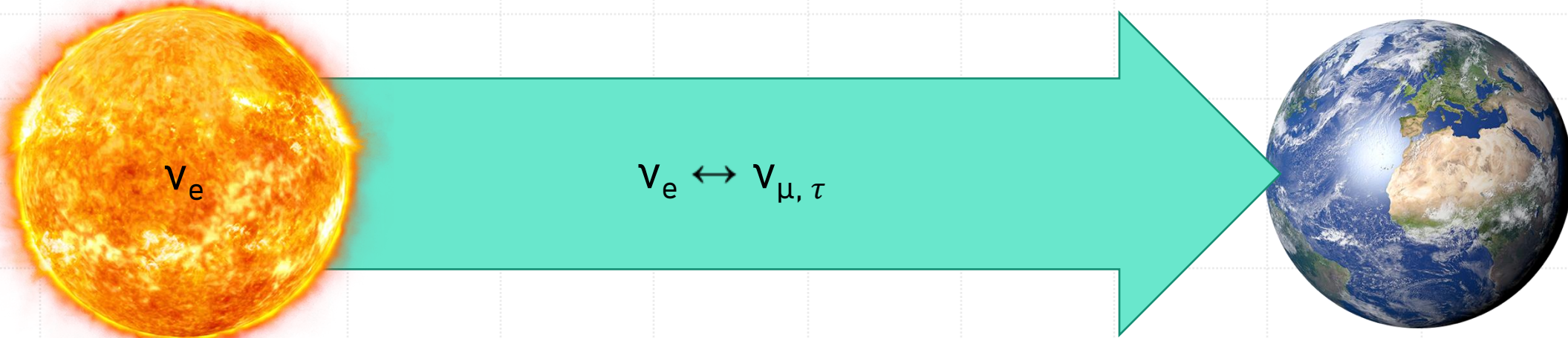
More Upcoming!

Including  $0\nu\beta\beta$

More upcoming!

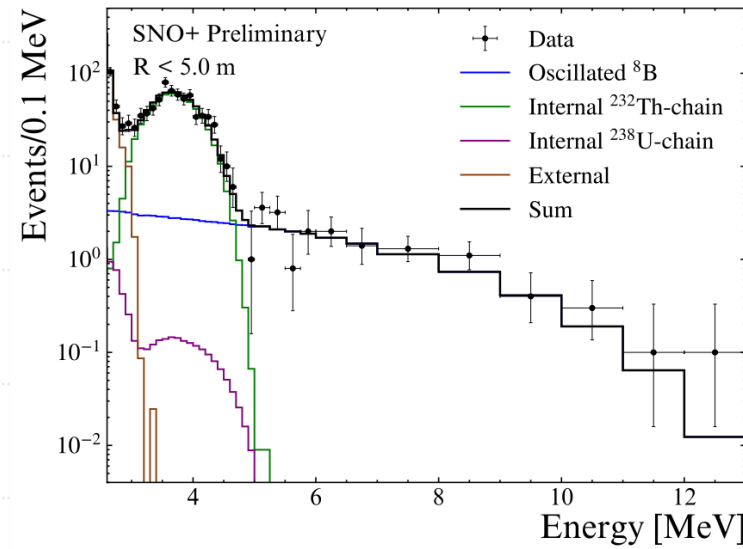
# Solar Neutrinos

$\nu_e$  CC and  $\nu_x$  NC elastic scattering



# Solar Neutrinos

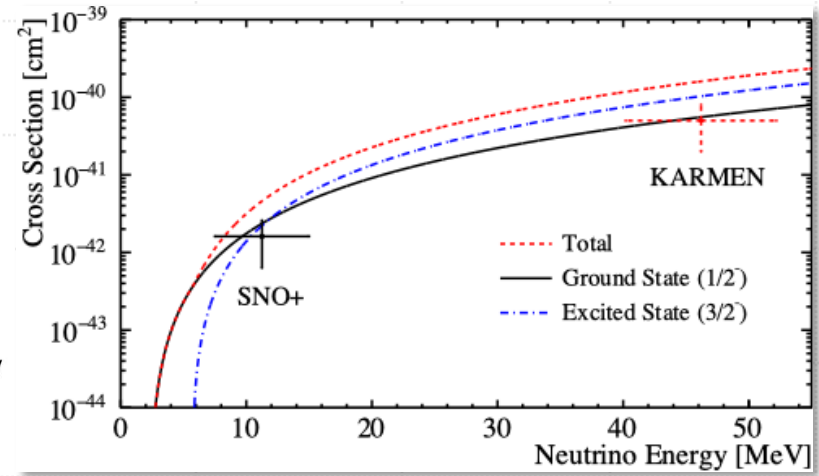
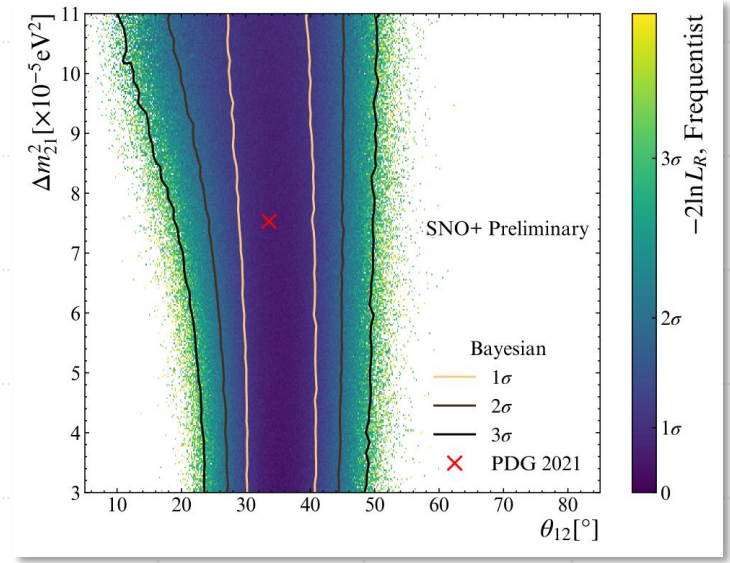
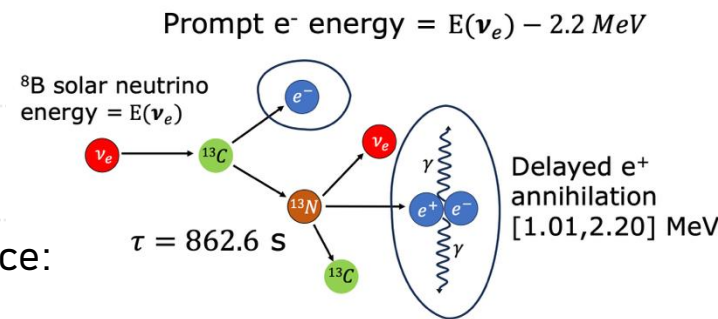
- $^8\text{B}$   $\nu$  ES on  $e^-$ :



- $^8\text{B}$   $\nu_e$  CC interaction on  $^{13}\text{C}$ :

(not previously measured)

Measured with  $4.2\sigma$  significance:  
[arXiv:2508.20844](https://arxiv.org/abs/2508.20844)

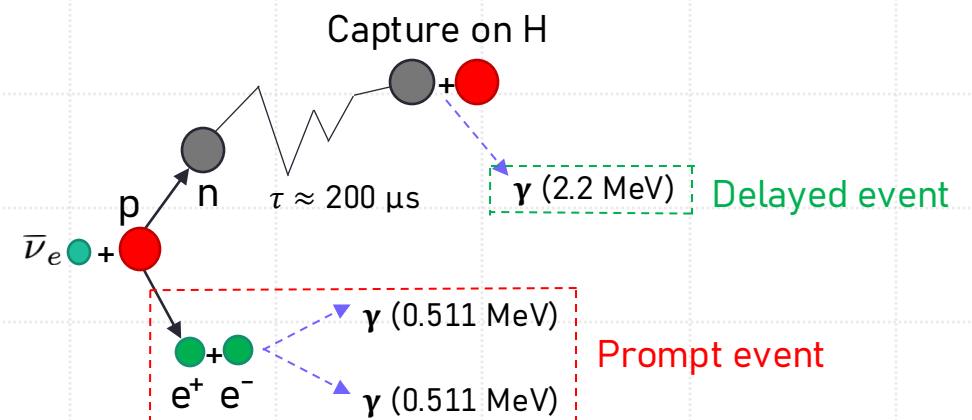




# Reactor Antineutrinos

- Prompt energy highly correlated to  $\bar{\nu}_e$  energy ( $E \approx E_{\nu} - 0.8 \text{ MeV}$ )
- Coincidence tagging eliminates most backgrounds

Cuts	Prompt	Delayed
Energy [MeV]	0.9 - 8.0	1.85 - 2.5
Radial position [m]	< 5.7	
$ \Delta\vec{r} $ [m]	< 2.5	
$\Delta t$ [ $\mu\text{s}$ ]	< 2000	
Likelihood ratio	> -3.5	
Data cleaning	pass	



➡ Expect 27.9 IBD events in 134.5 days (PDG2021 oscillation).

➡ 0.3 accidental coincidences expected from un-correlated backgrounds

# Geo-Neutrinos

- Produced from radioactive decays in the Earth.
- Produce IBDs.
- Large uncertainty** in the flux, depends on the Earth model.

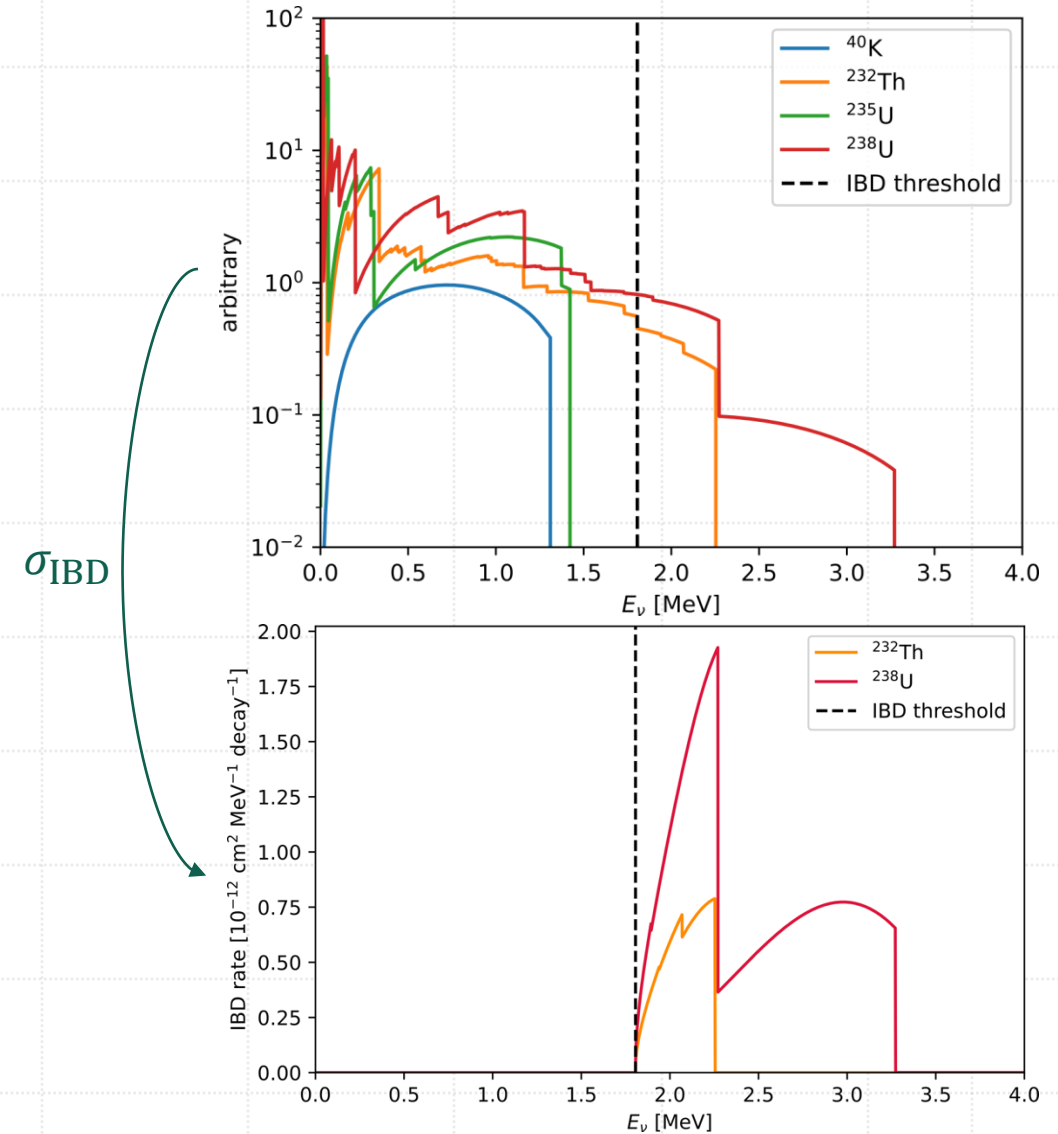
➔ Effectively **fit the geo-ν flux simultaneously**.

- Oscillation averaged out over all distances:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = s_{13}^4 + c_{13}^4 (1 - 2s_{12}^2 c_{12}^2)$$

- U/Th ratio roughly constrained:  $R_{U/Th} = 3.7 \pm 1.3$
- As prior estimate, assume Mid-Q flux from Wipperfurth code, with CUC of Strati et. al.: 46 TNU

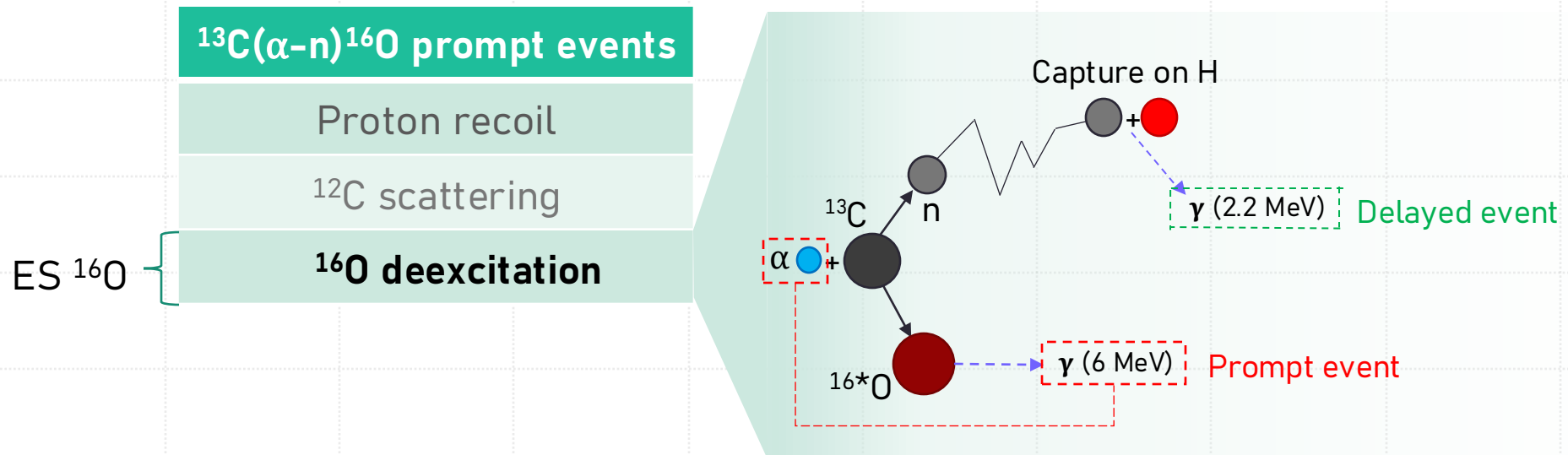
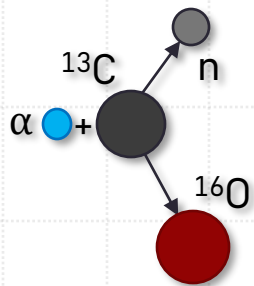
➔ Expect 7.2 events in 134.5 days



CUC = Close Upper Crust

# Background: ( $\alpha$ , n) Events

Triggered by  $\alpha$  particles from  $^{210}\text{Po}$  decays capturing on  $^{13}\text{C}$  inside the detector:

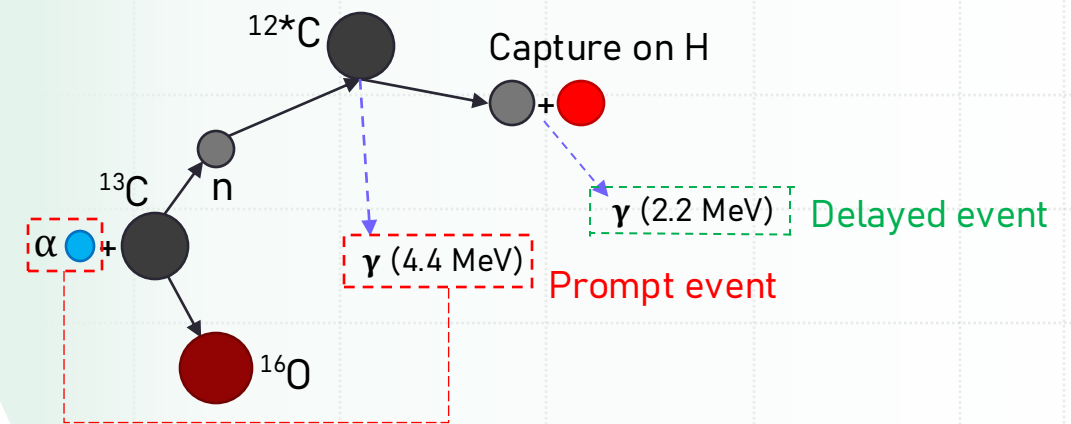
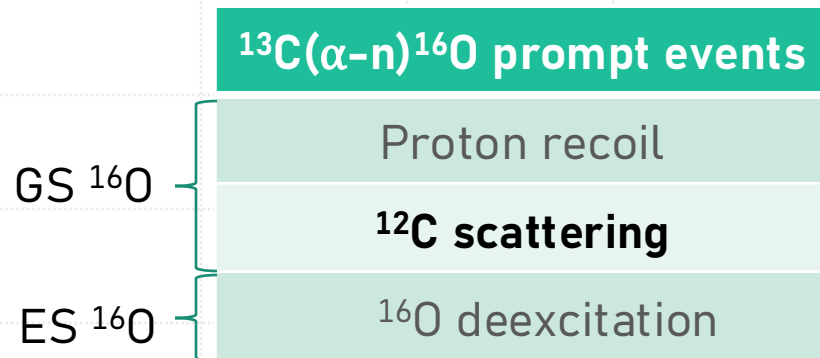
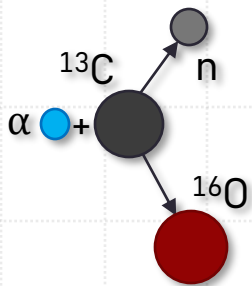


Prompt + neutron capture mimics IBD!

- Oxygen produced in excited state(s).
- Releases  $\gamma$  or  $e^-e^+$  pair  **$\sim 6$  MeV**.

# Background: ( $\alpha$ , n) Events

Triggered by  $\alpha$  particles from  $^{210}\text{Po}$  decays capturing on  $^{13}\text{C}$  inside the detector:

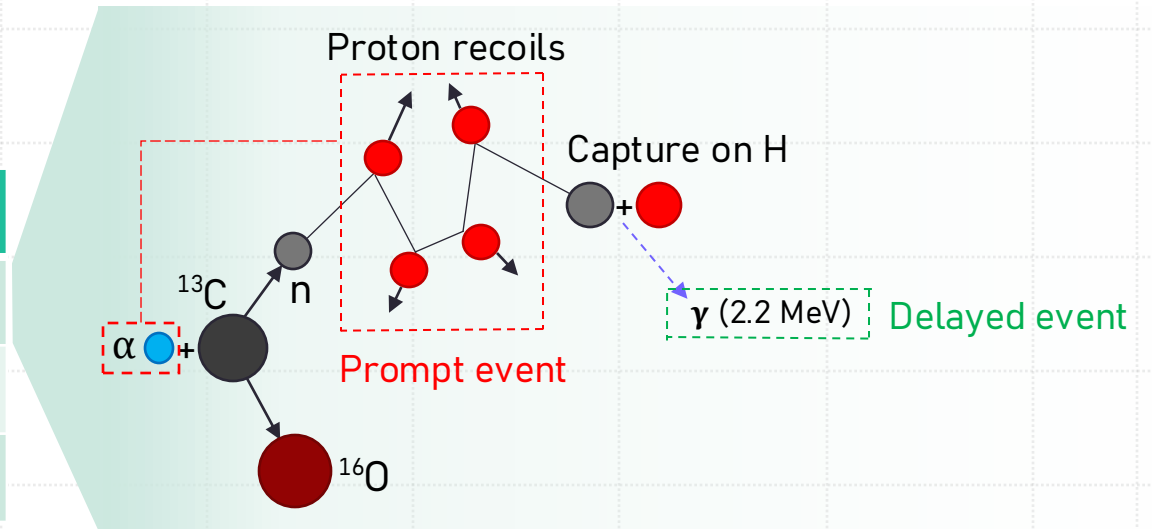
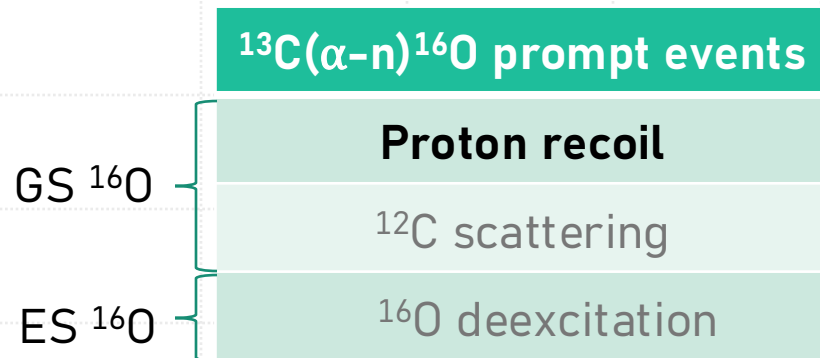
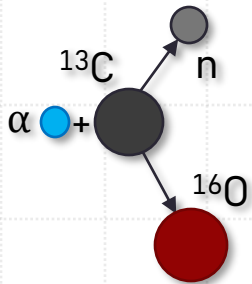


Prompt + neutron capture mimics IBD!

- Oxygen produced in ground state.
- Neutron takes away most of the energy.
- Inelastically scatters off  $^{12}\text{C}$  in medium.
- Releases **4.4 MeV  $\gamma$** .

# Background: ( $\alpha, n$ ) Events

Triggered by  $\alpha$  particles from  $^{210}\text{Po}$  decays capturing on  $^{13}\text{C}$  inside the detector:

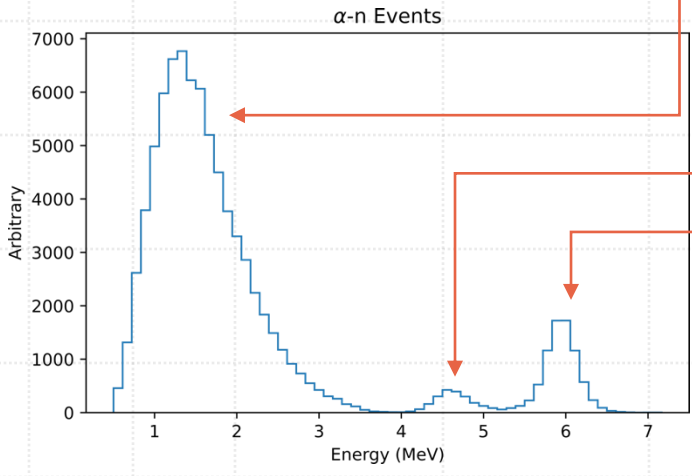
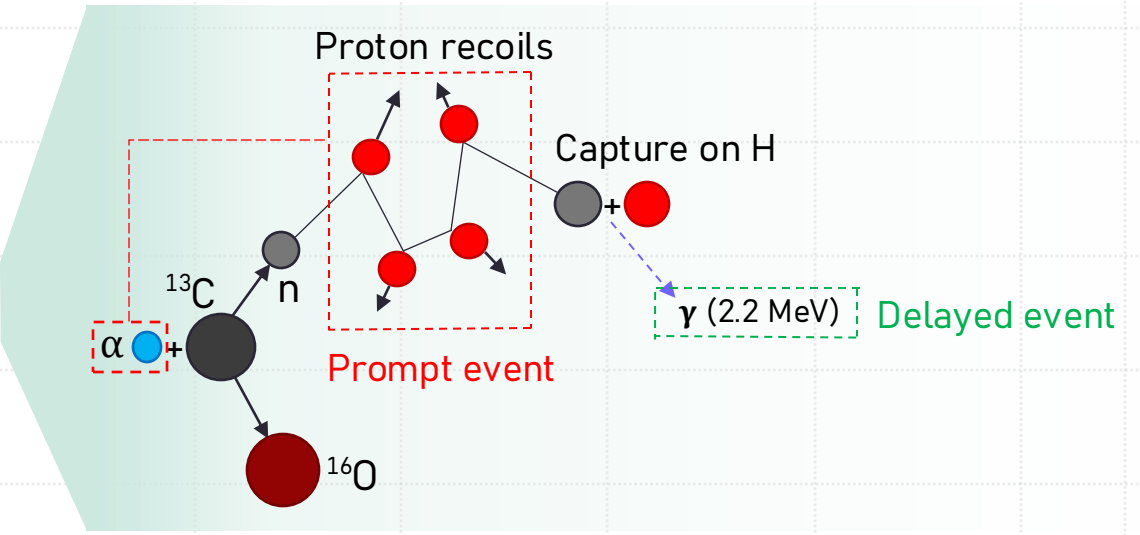
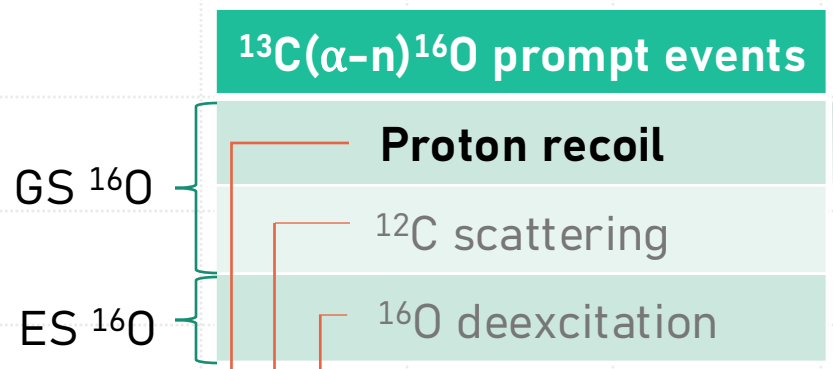
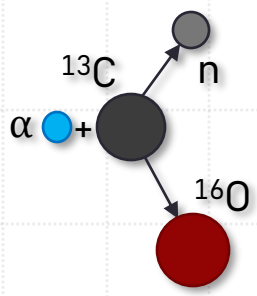


Prompt + neutron capture mimics IBD!

- Elastically scatter of protons (for a few ns).
- Reconstructed events in **0.4–3.5 MeV range**.

# Background: ( $\alpha$ , n) Events

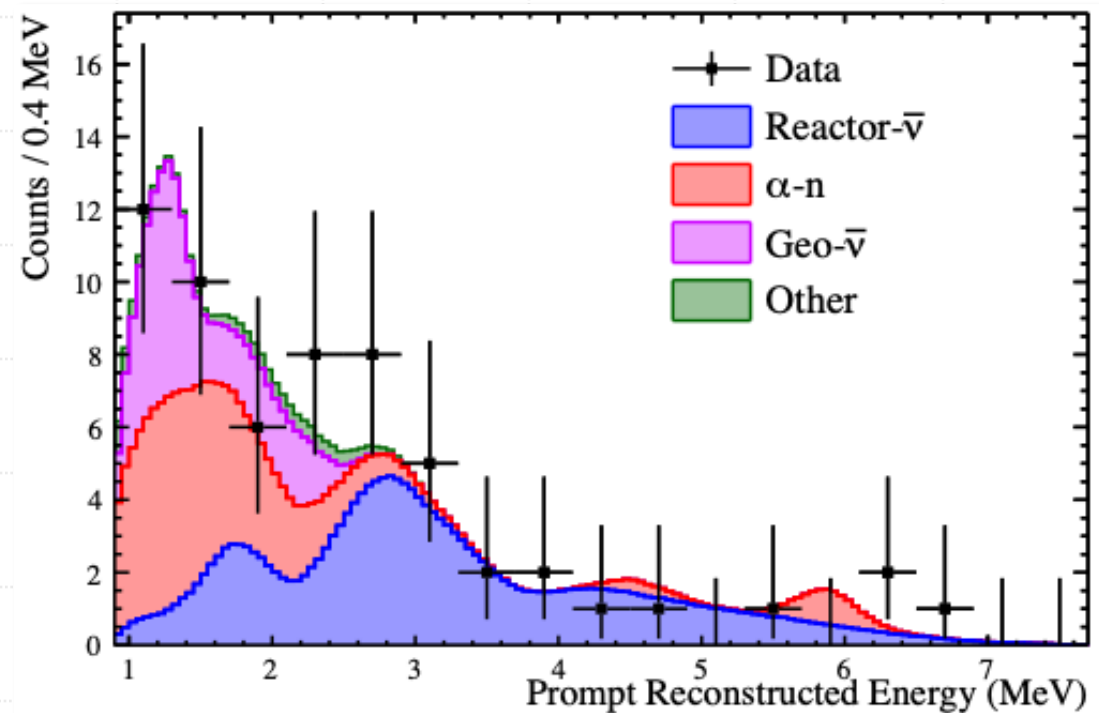
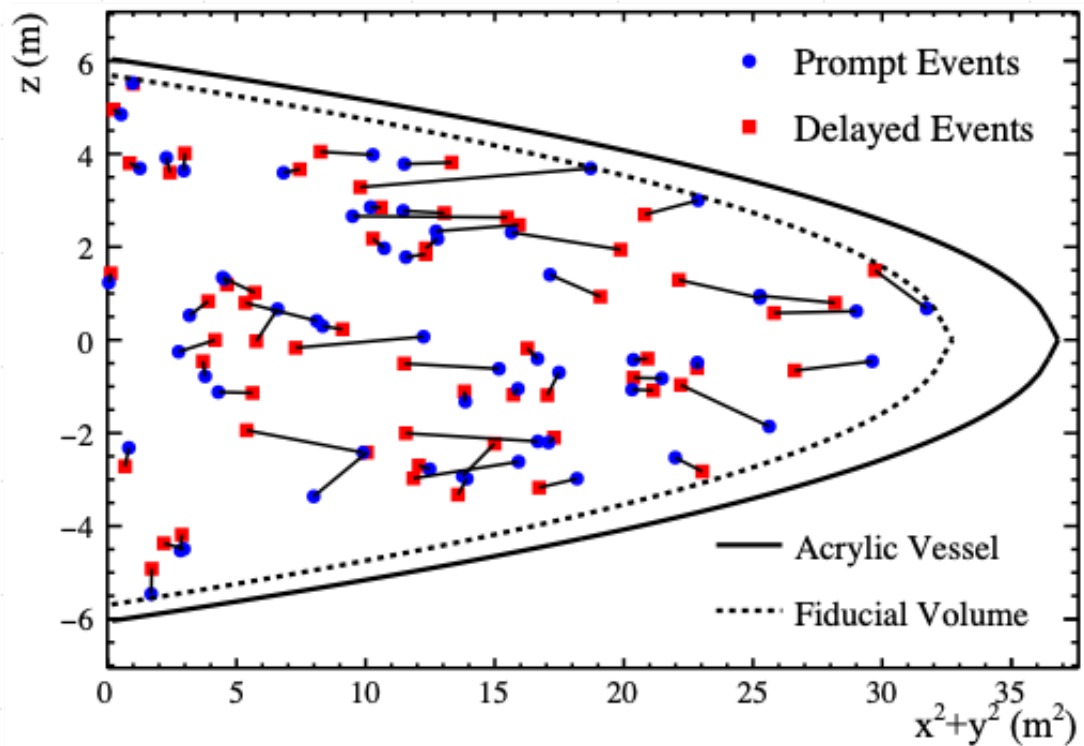
Triggered by  $\alpha$  particles from  $^{210}\text{Po}$  decays capturing on  $^{13}\text{C}$  inside the detector:



Expect 18.2 events in 134.5 days.

# Reactor Antineutrinos

- Coincidence tagging of IBD events
- 59 events tagged in 134.5 days of the initial scintillator phase (expected 54.7):

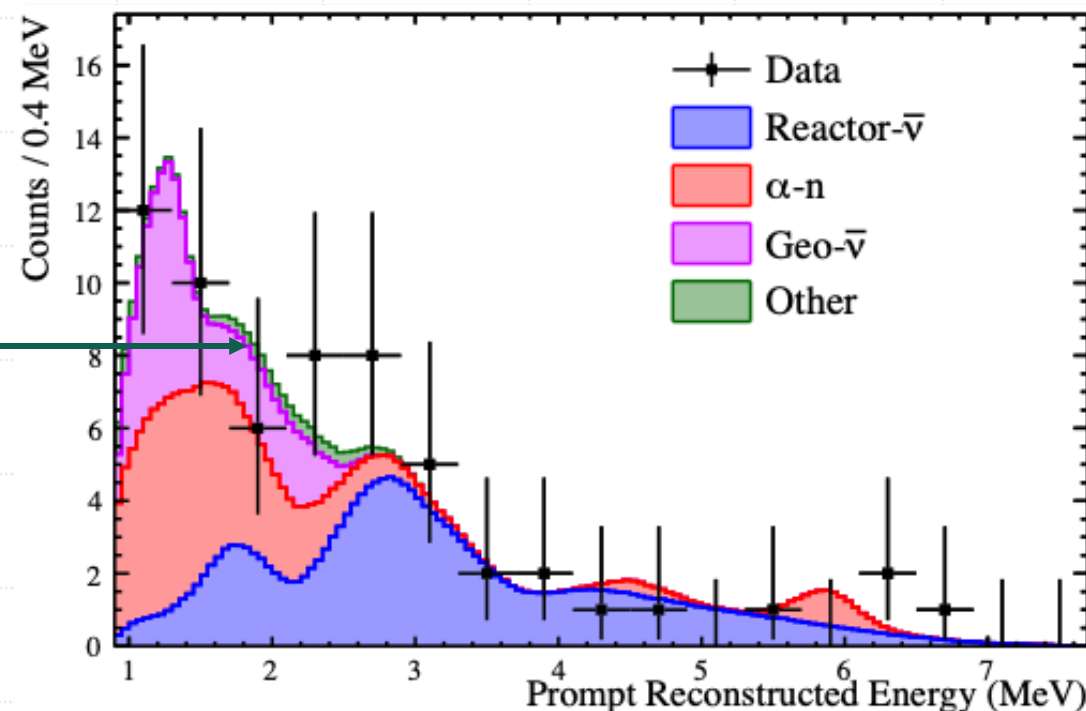
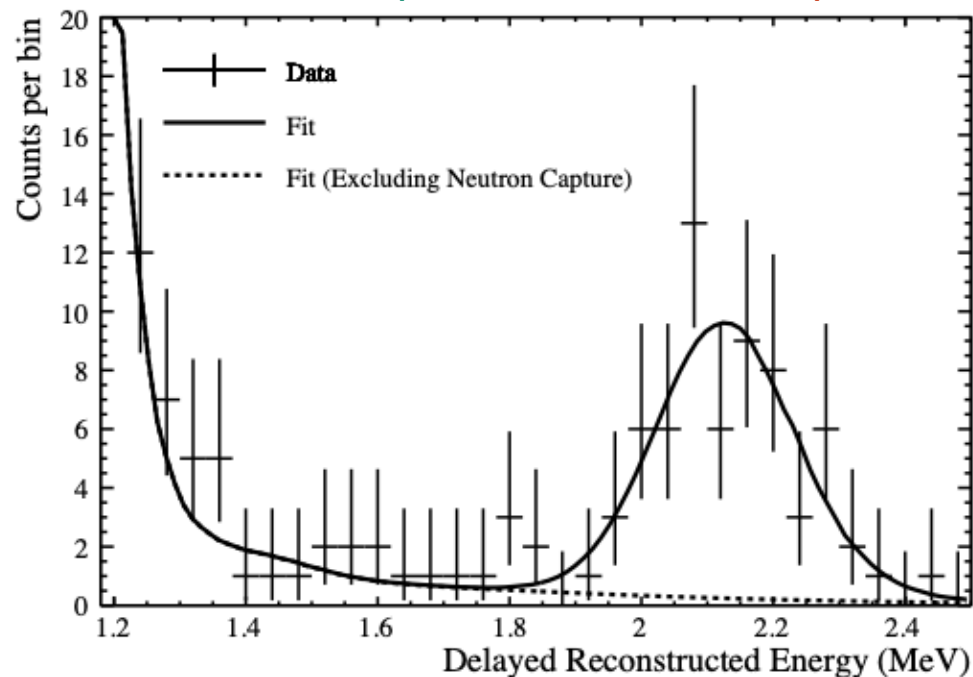
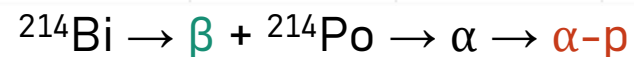


# Reactor Antineutrinos

- Events observed in low energy sideband of delayed events.
- Use data-driven model to estimate leakage in neutron capture sample.
- Likely caused by  $\alpha$ -p scatters:

prompt

delayed



# Reactor Antineutrinos

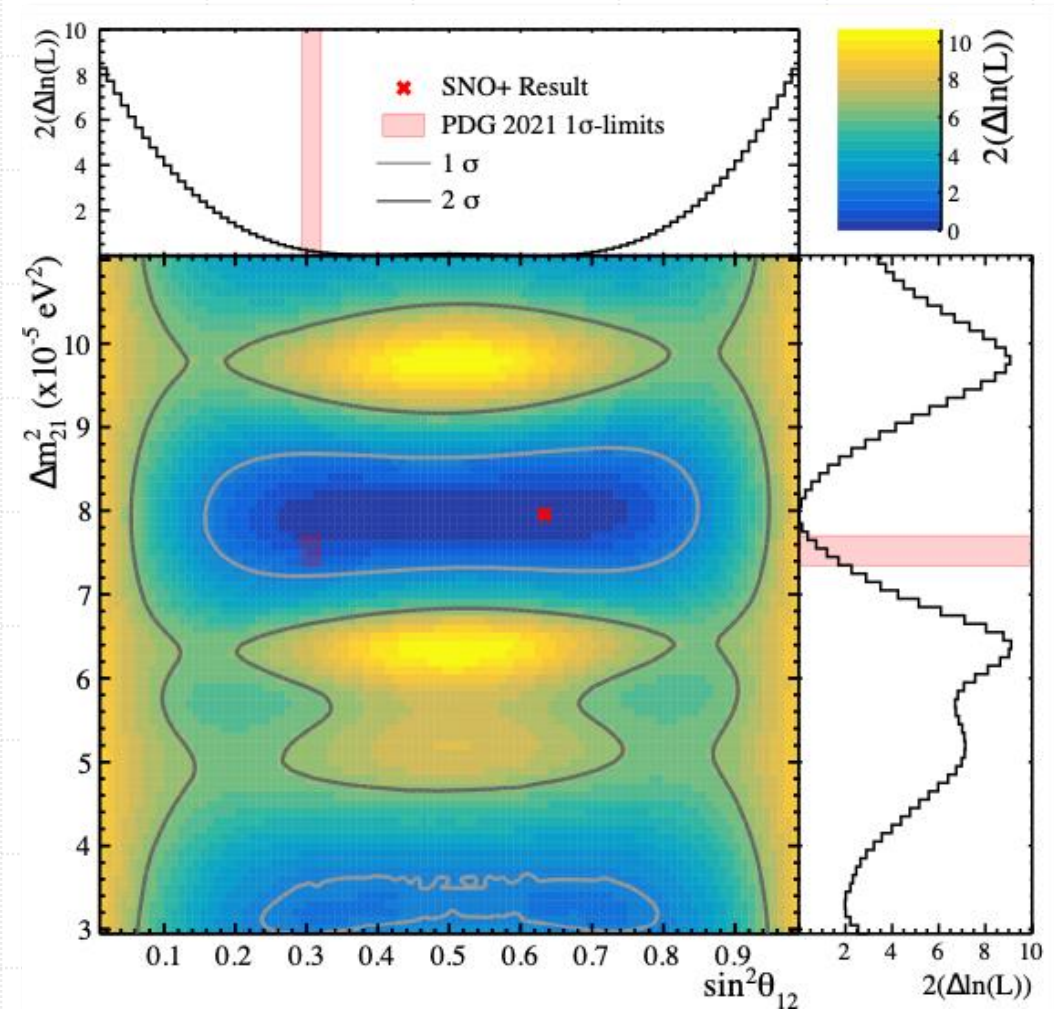
- Oscillation analysis
- Measure long-baseline oscillation:

$$\Delta m_{21}^2 = 7.96_{-0.42}^{+0.48} \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{12} = 0.62_{-0.40}^{+0.16}$$

- Constrain oscillation (PDG 2021), fit geo-neutrino flux:

$$\Phi_{\text{geo-}\nu} = 73_{-43}^{+47} \text{ TNU}$$



# Reactor Antineutrinos

- Oscillation analysis
  - Measure long-baseline oscillation:
- $$\Delta m_{21}^2 = 7.96^{+0.48}_{-0.42} \times 10^{-5} \text{ eV}^2$$
- $$\sin^2 \theta_{12} = 0.62^{+0.16}_{-0.40}$$
- Constrain oscillation (PDG 2021), fit geo-neutrino flux:

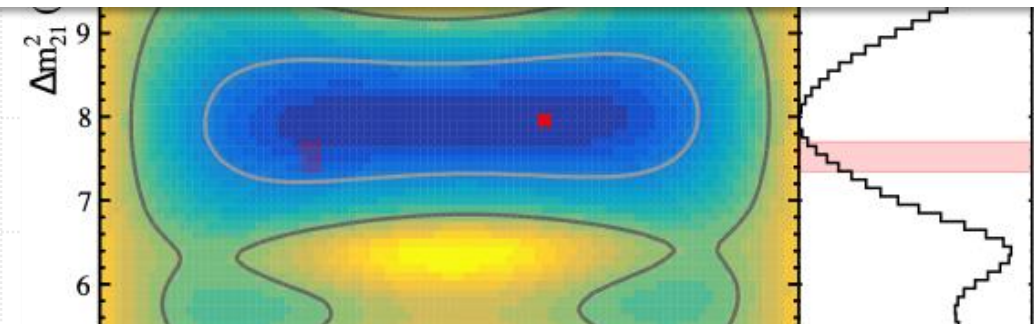
$$\Phi_{\text{geo-}\nu} = 73^{+47}_{-43} \text{ TNU}$$

2<sup>nd</sup> most precise measurement, behind KamLAND:

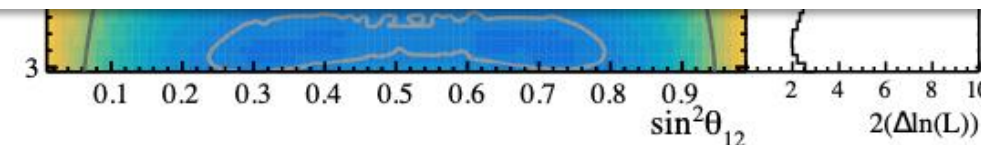
$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$$

Consistent with combined solar neutrino results:

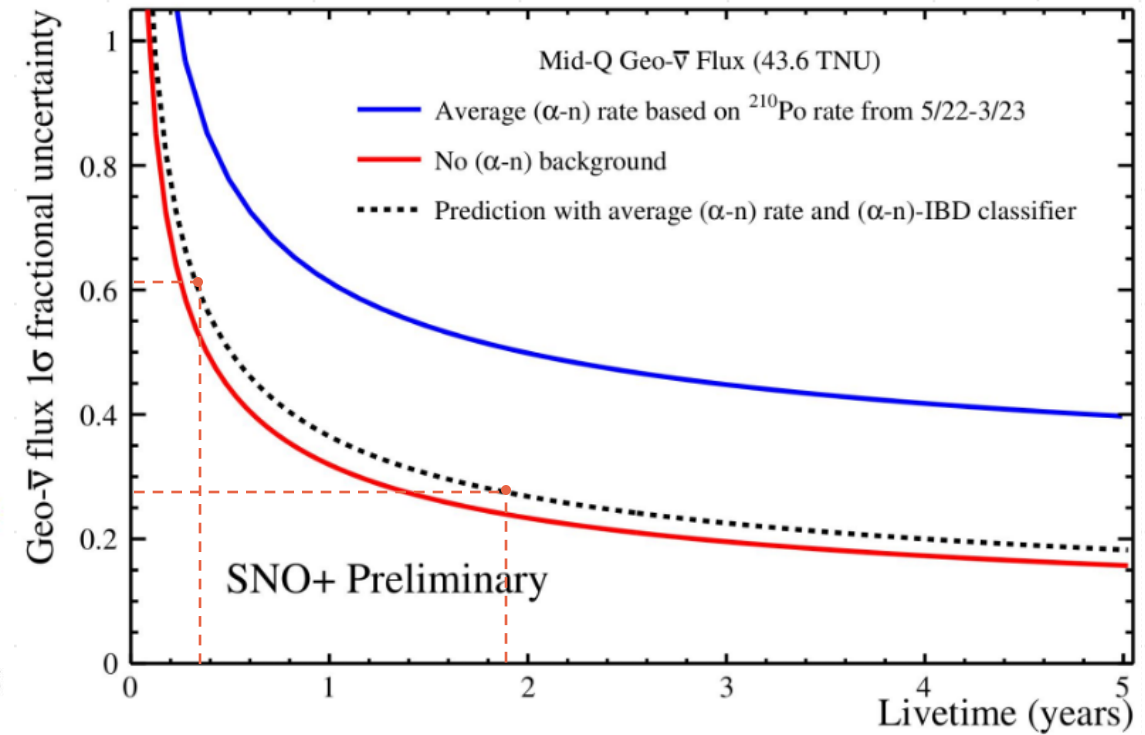
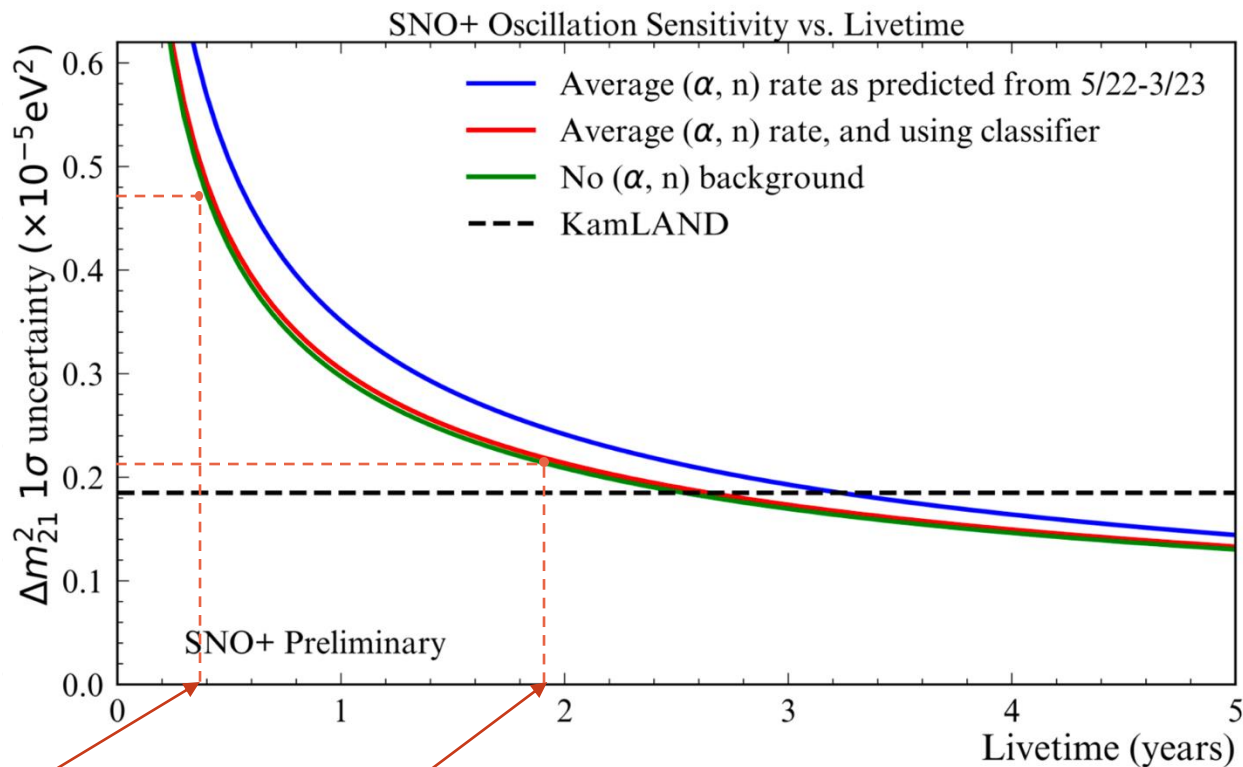
$$\sin^2 \theta_{12} = 0.308 \pm 0.013$$



3<sup>rd</sup> measured location worldwide (Italy, Japan)



# Upcoming Results



Previous analysis  
(134.5 days)

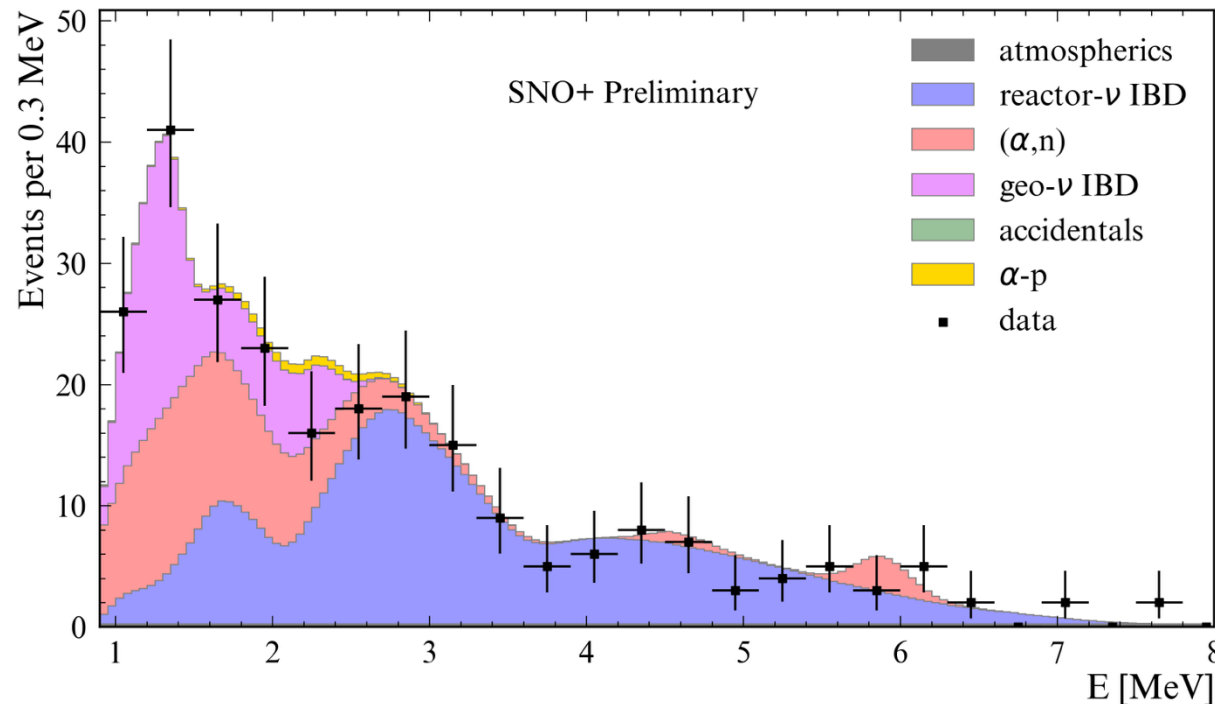
Next analysis  
(245.8 + 439.4 days)

➡ Initial scintillator phase (245.8 days) and enhanced scintillator phase (439.4 days):  
greater light yield (added bis-MSB).

# Upcoming Results

- Tagged 103 + 143 IBD candidates
- Fit oscillation parameters with strong constraints from best-fit values from PDG2025
- Fit backgrounds with constraints
- Geo- $\nu$  flux is fit (unconstrained)

Combined spectrum (initial + enhanced scintillator phases)



$$\Phi_{\text{geo-}\nu} = 73_{-43}^{+47} \text{ TNU}$$



$$\Phi_{\text{geo-}\nu} = 61_{-22}^{+22} \text{ TNU}$$

(1.33 times Mid-Q model, 36% uncertainty)

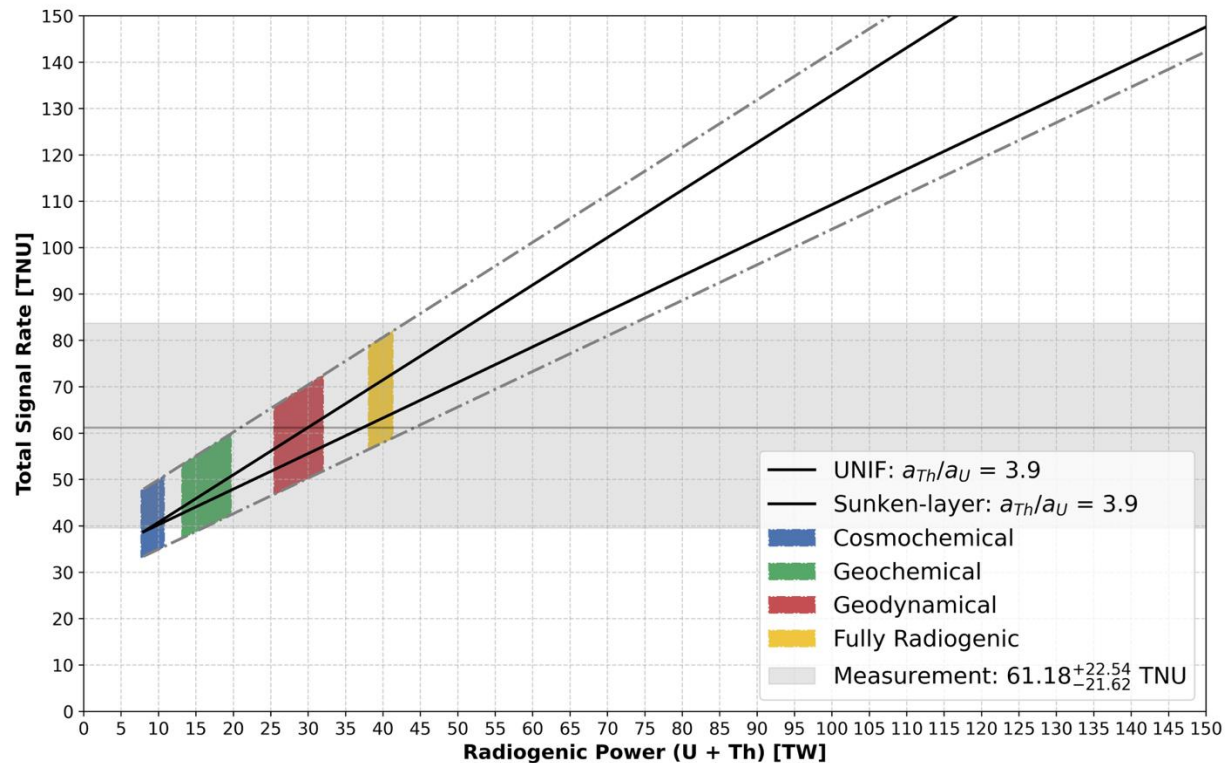
$$R_{\text{U/Th}} = 3.3_{-1.4}^{+1.4}$$

# Upcoming Results

Fit total geo- $\nu$  signal as a function of radiogenic heat production:

$$\Phi_{\text{geo-}\nu} = 61_{-22}^{+22} \text{ TNU}$$

Heat Power vs. Total Signal Rate Comparison @ SNO+ (Enomoto)

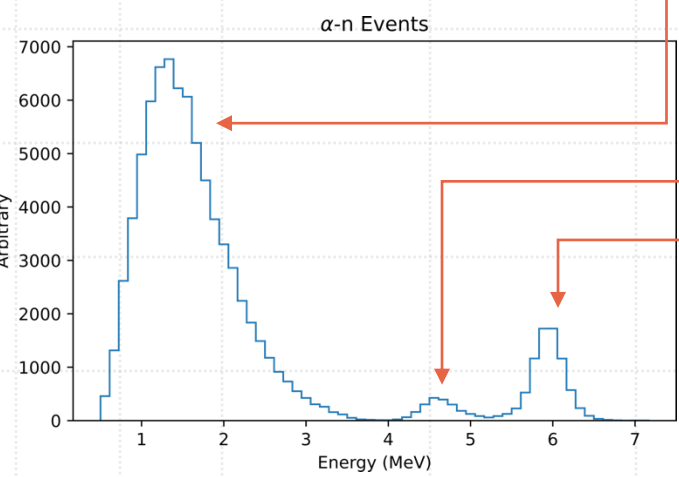
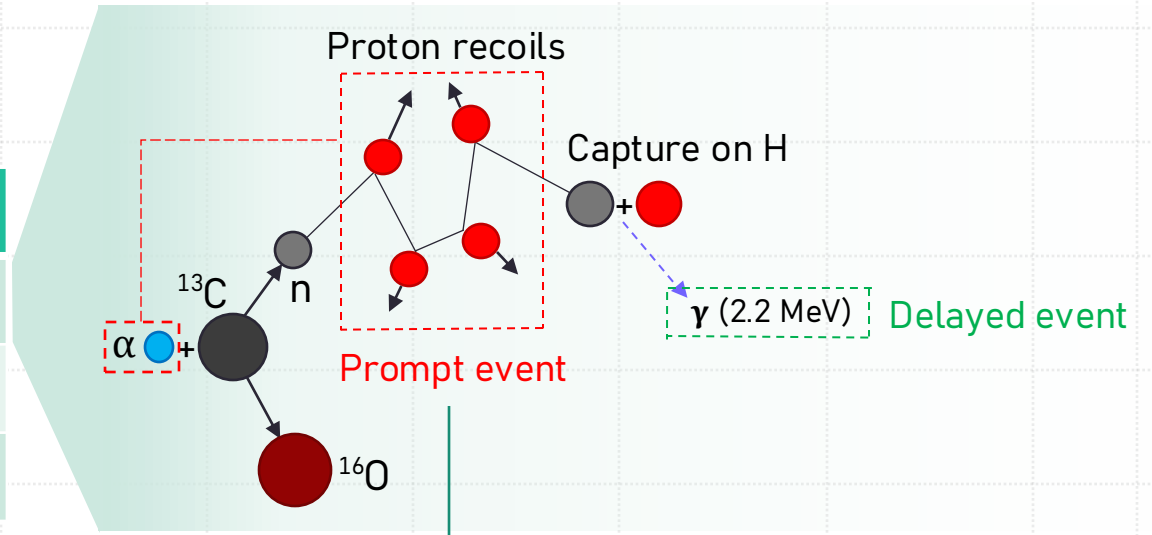
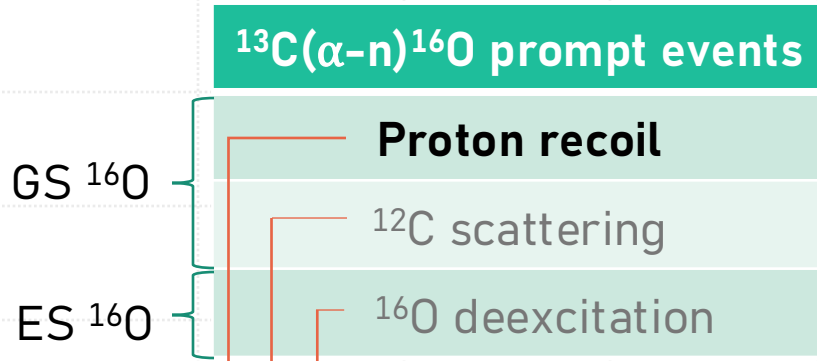
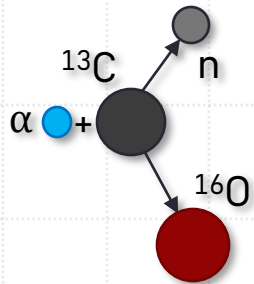


Fit 49.5 geo- $\nu$  IBD events:

- Close to Borexino's 52.6 ([10.1103/PhysRevD.101.012009](https://arxiv.org/abs/10.1103/PhysRevD.101.012009))
- Match KamLAND's 116 with around 5 years of livetime ([10.1103/PhysRevD.88.033001](https://arxiv.org/abs/10.1103/PhysRevD.88.033001)).

# Recall: ( $\alpha, n$ ) Events

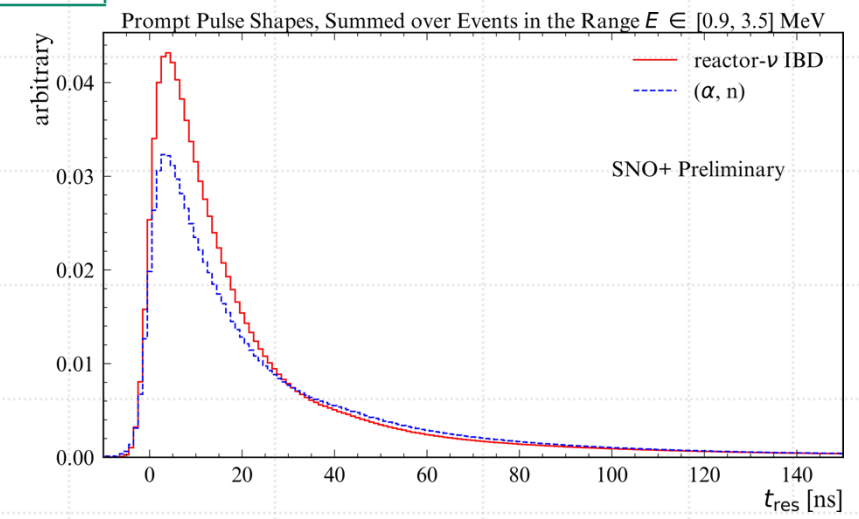
Triggered by  $\alpha$  particles from  $^{210}\text{Po}$  decays capturing on  $^{13}\text{C}$  inside the detector:



longer process & different scintillator response

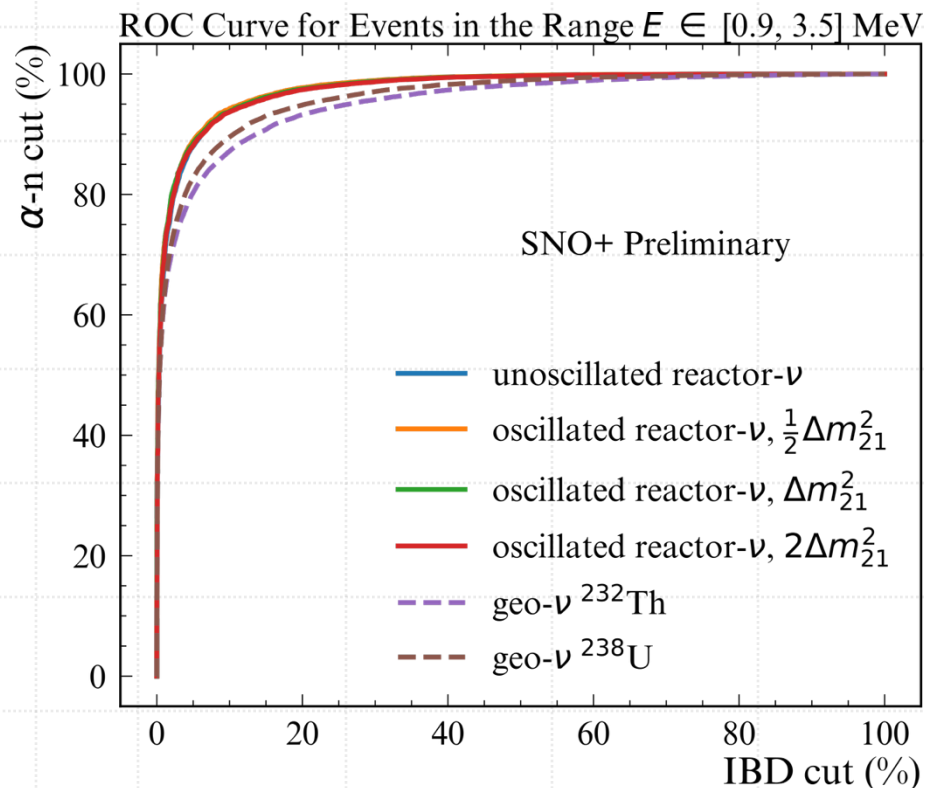
→ different pulse shape:

→ Expect 16.5 events in 134.5 days.



# $(\alpha, n)$ -IBD Classifier

- Created event-by-event classifier based on the Fisher discriminant
- Performance characterized in MC simulations:



➔ Can **cut 90% of  $(\alpha, n)$** , and only sacrifice:

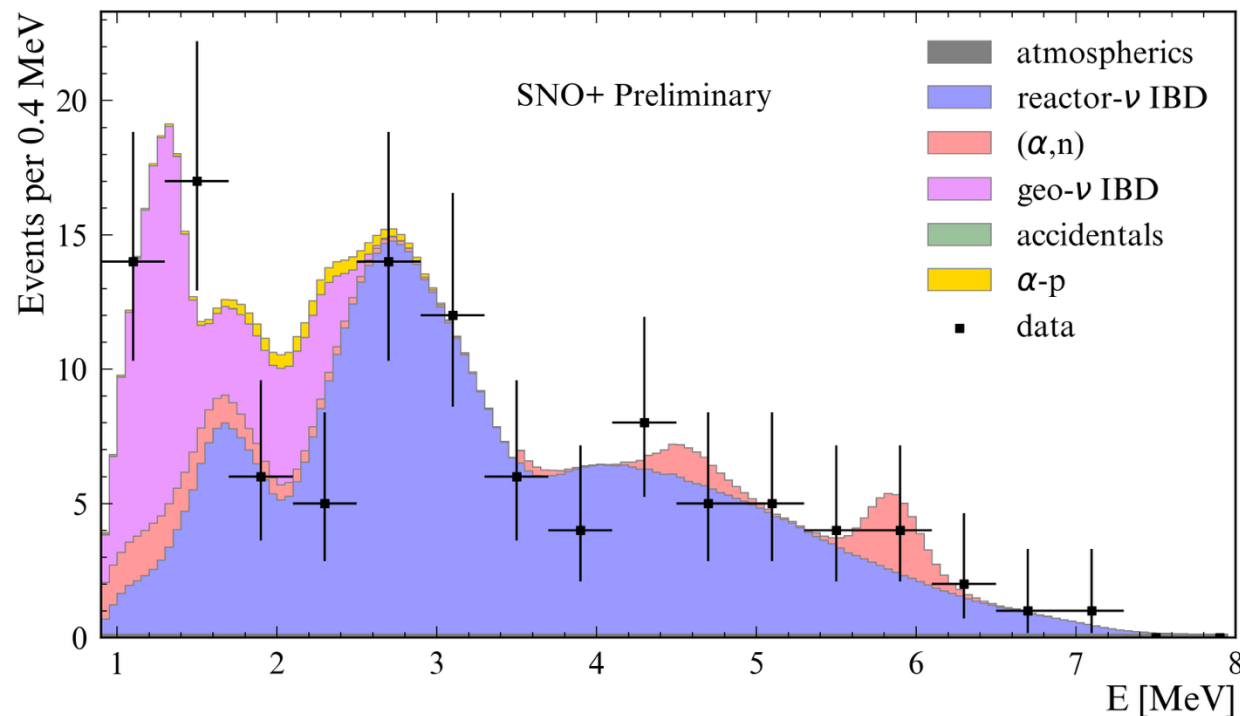
- ~6% reactor- $\nu$  IBDs
- ~11% geo- $\nu$  IBDs

➔ Finalising systematic uncertainties with calibration data

# Upcoming Results

- Fit oscillation parameters with strong constraints from best-fit values from PDG2025
- Geo- $\nu$  flux unconstrained
- Fit backgrounds with constraints
- Applied  $(\alpha, n)$ -IBD classifier

Enhanced scintillator phase only



Finalising systematic  
uncertainty estimation

# Summary

- SNO+ is a multipurpose, low-background detector
- Te-loading starting early 2026  $\rightarrow 0\nu\beta\beta$
- Solar neutrino results ( $^8\text{B}$  flux, oscillation,  $^{13}\text{C}$  interaction)
- Reactor antineutrinos: 2<sup>nd</sup> most precisely measured  $\Delta m^2_{21}$
- Geo-neutrino measurement
- More precise measurements very soon!

