LIVERPOOL HEP (DEFERRED) CHRISTMAS MEETING

28/04/2021

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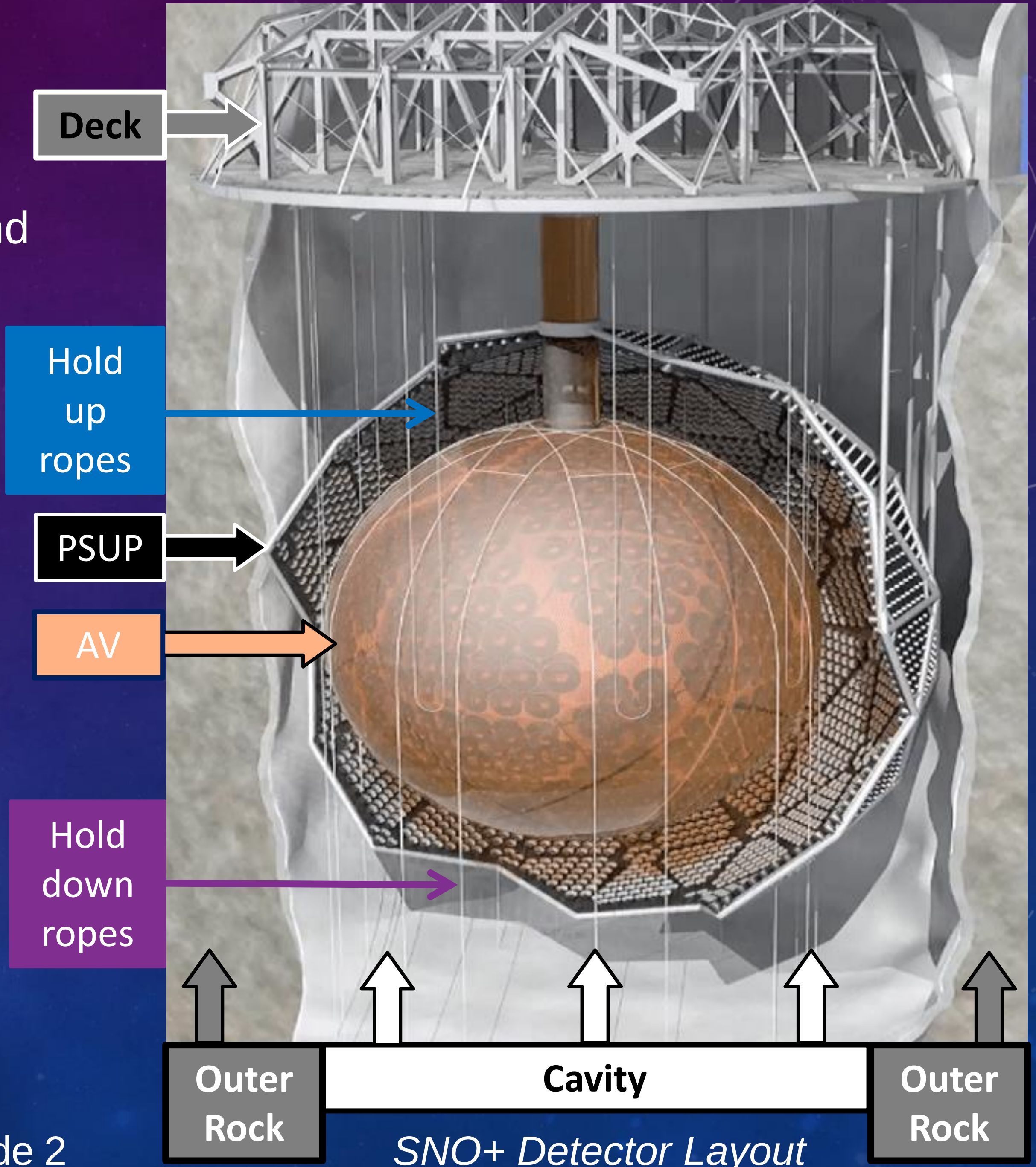
SNO+ EXPERIMENT OVERVIEW

- SNO+ is a neutrino detector based 2km underground
  - Low cosmic background: ~65 muons each day
- Upgraded from SNO (Nobel prize winning) experiment
- Main scientific goal:
  - **Neutrinoless double beta decay ($0\nu\beta\beta$)**
- Several other scientific goals, including:
  - ***Antineutrino studies***
  - Supernova & Solar neutrino observations
  - Invisible nucleon decay (ND) studies



SNO+ Detector Layout

SNO+ EXPERIMENT PHASES & FILLING

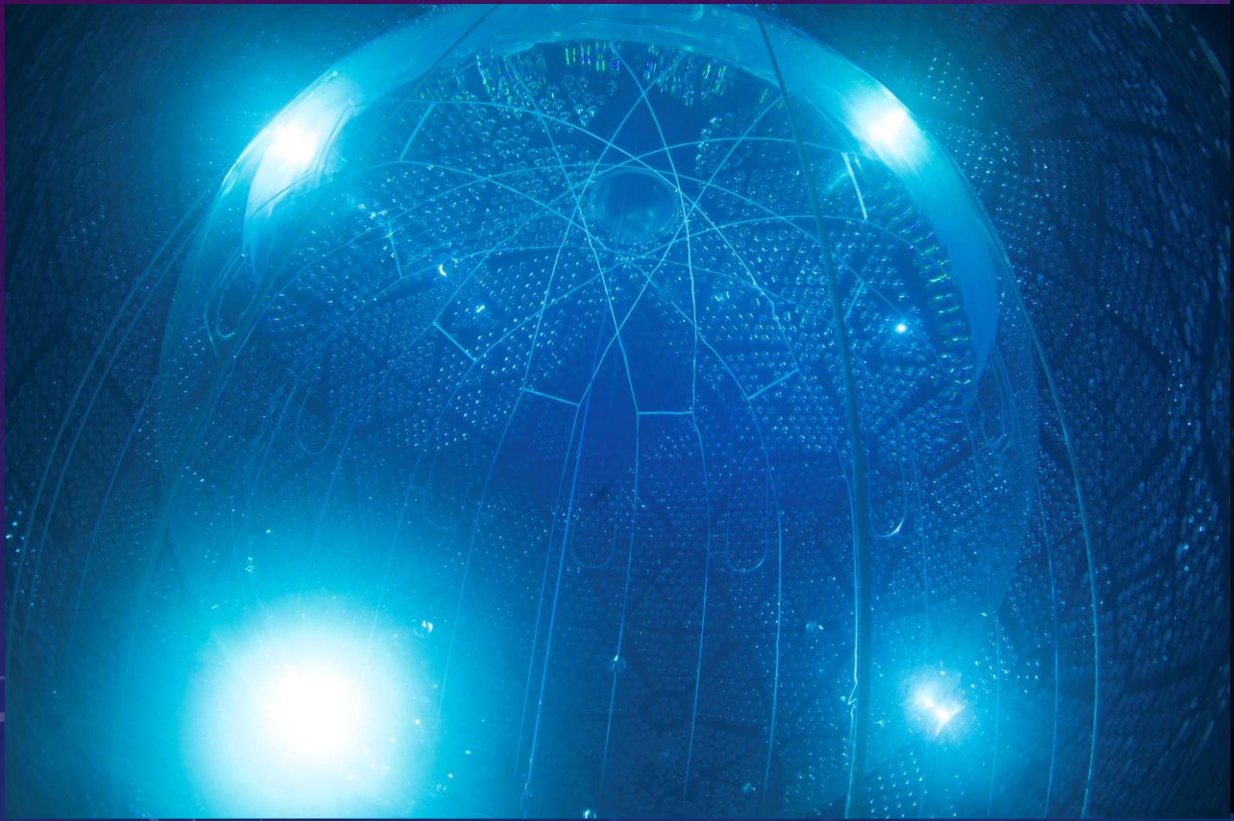
Three main phases to SNO+:

- Water Cherenkov – 900 tonnes of Ultra Pure Water
~ 2 years of data taken (May 2017 – July 2019)

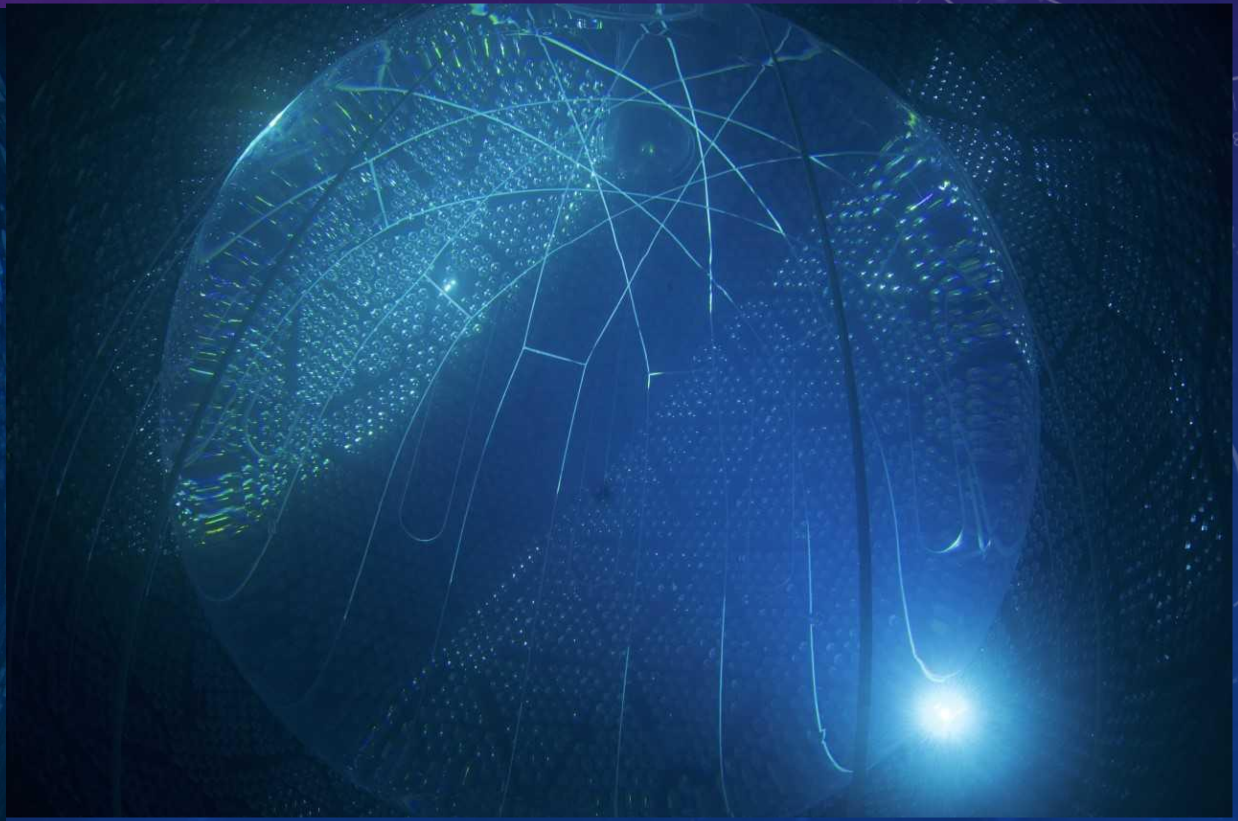
*Phase 1.5: ***Current Analysis Period***
Detector partially filled with 364 tonnes of LAB + Fluor PPO (March 2020 – October 2020)

- Pure Liquid Scintillator – 780 tonnes of LAB + PPO
Detector is now "full" → Yay! :-D

- Tellurium Doped Liquid Scintillator – additional 3.9 tonnes of Te (i.e. 1.3 tonnes of ^{130}Te)
- 5 years of predicted data taking



364 tonnes of LAB (Phase 1.5)



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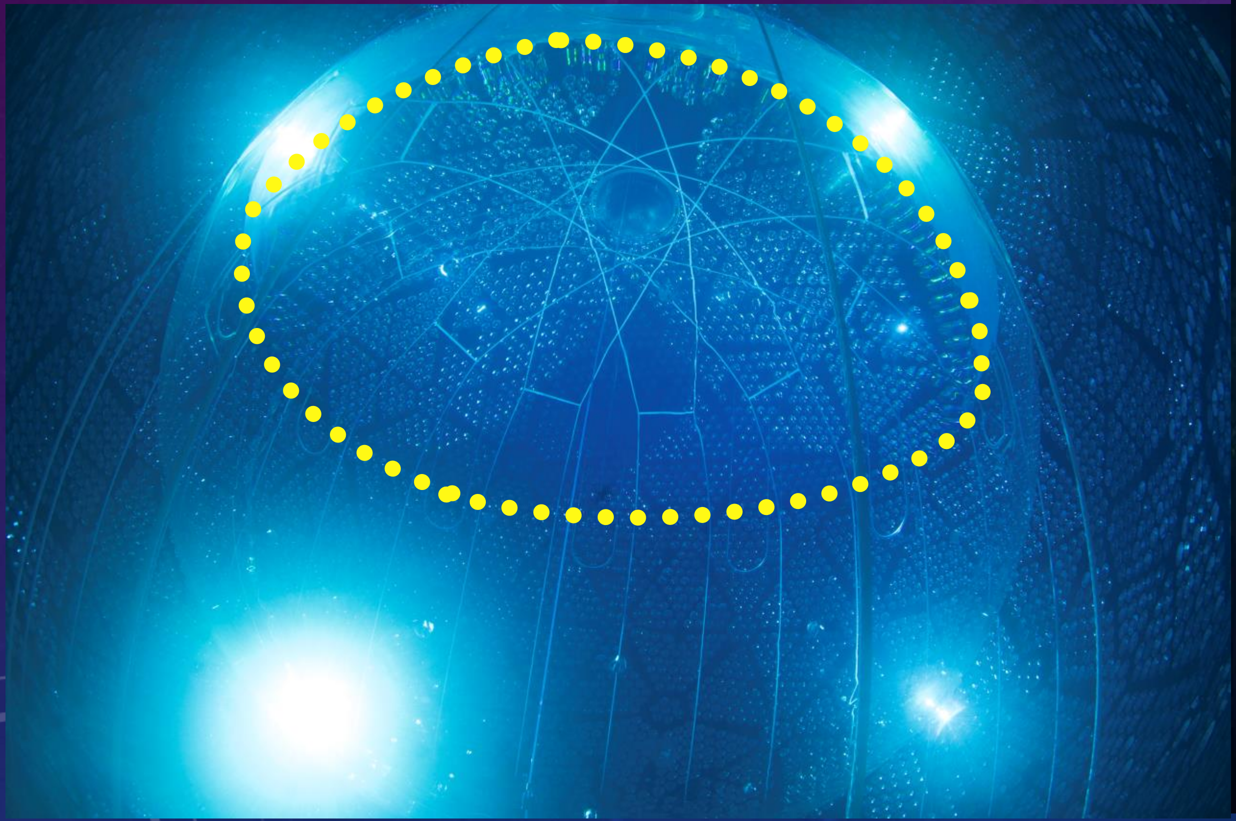

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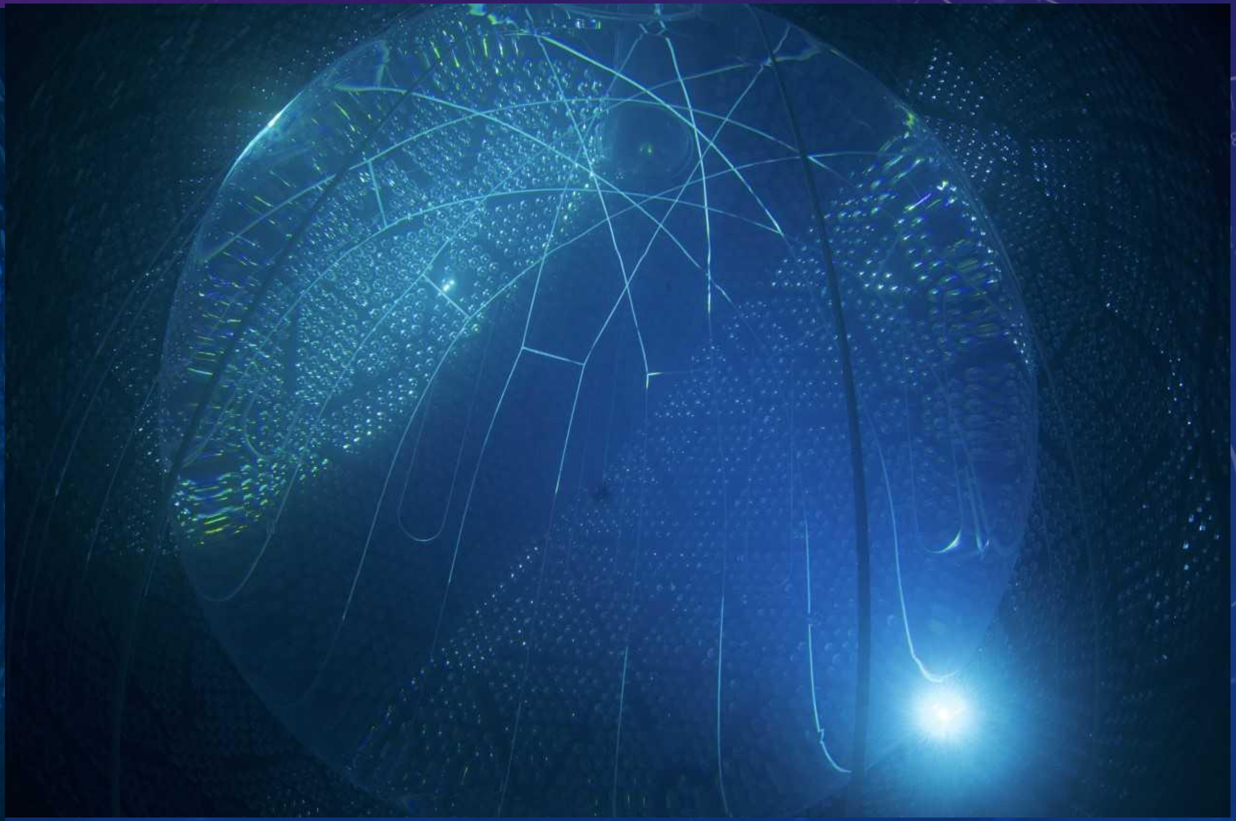

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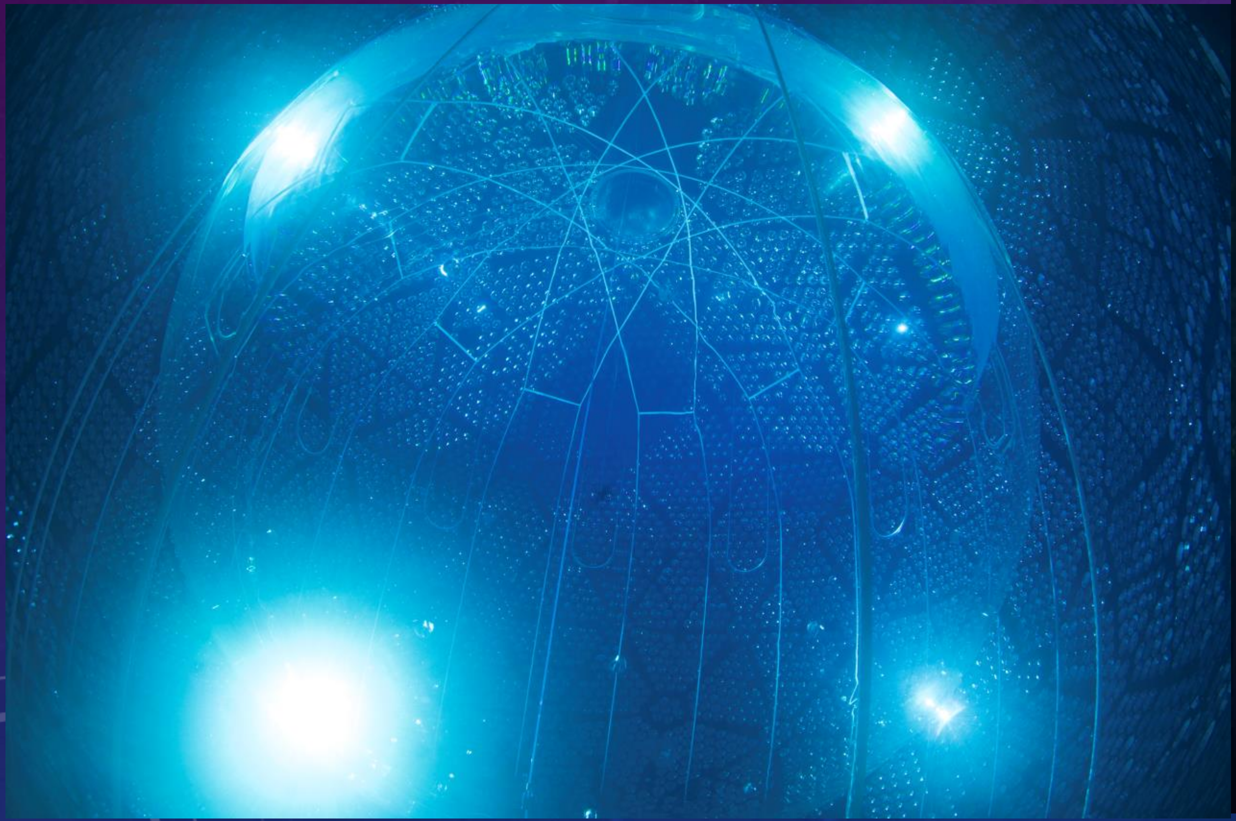

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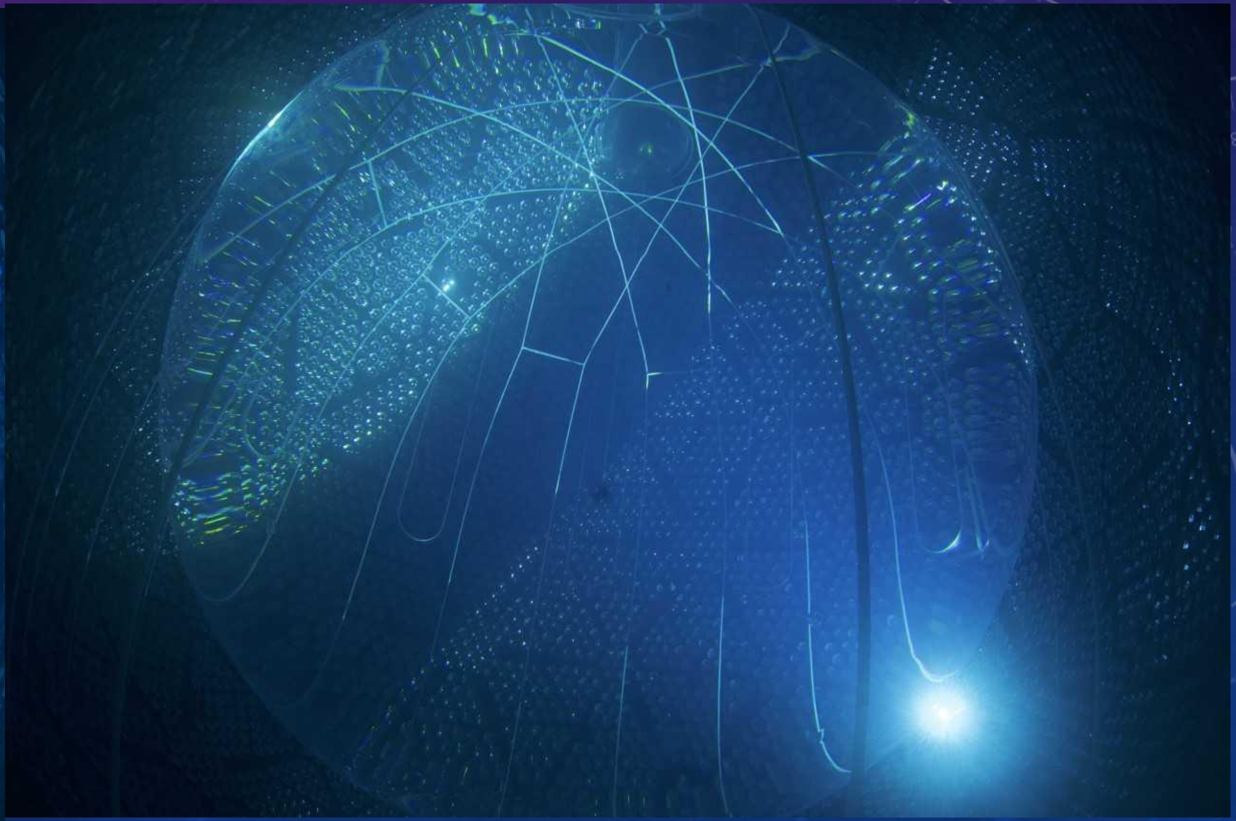
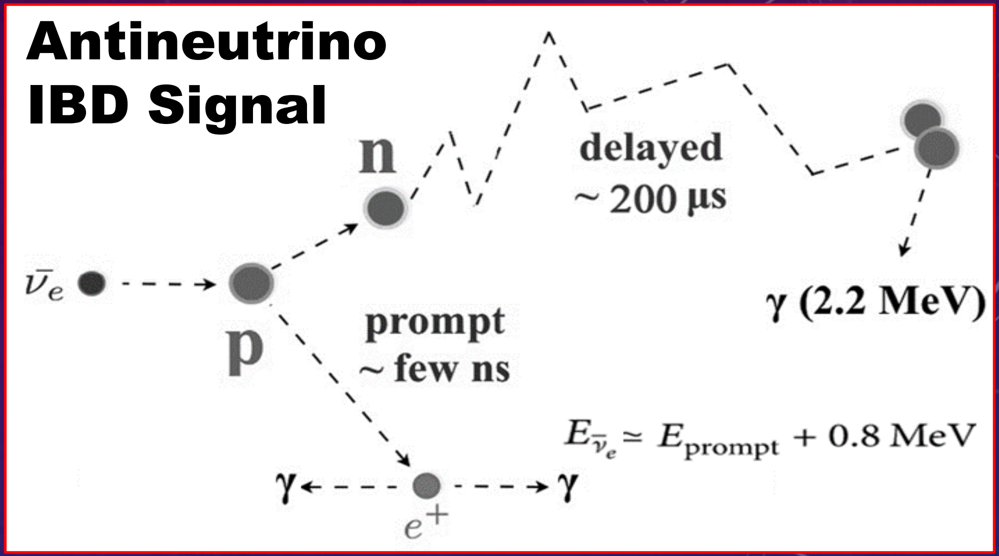


780 tonnes of LAB (Fully Filled)

STUDIES AT LIP - LISBON

(α,n) BACKGROUND IN SNO+

- All α-decays in the detector contribute to (α,n) background, Sources include:
  - Intrinsic scintillator purity
  - Introduction of Rn and Po during filling
  - Rn ingress
  - Leaching of Rn daughters from AV
- ***^{210}Po*** is the dominant α source
- (α,n) reactions act as a background for multiple SNO+ studies
- **Dominant background for Antineutrino analysis**
  - (α,n) mimics Inverse Beta Decay (IBD) signals



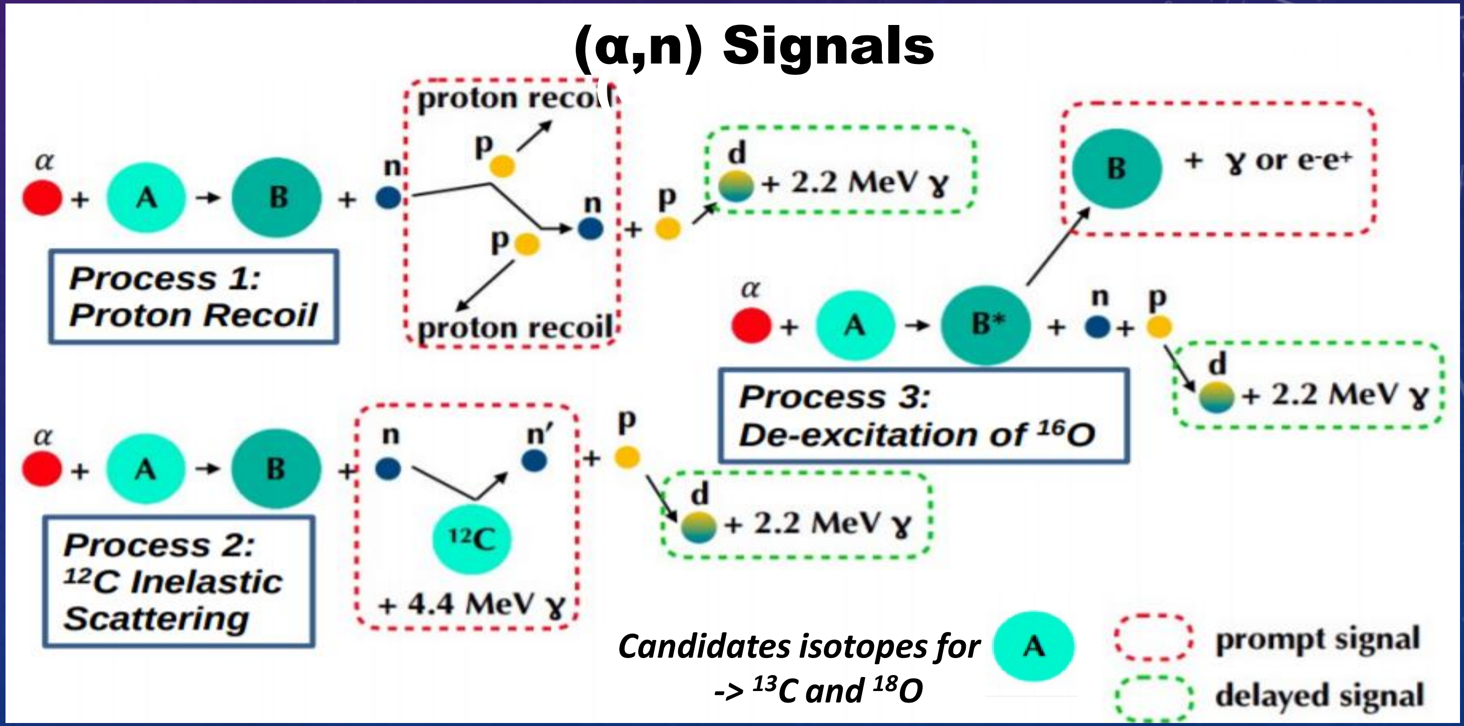


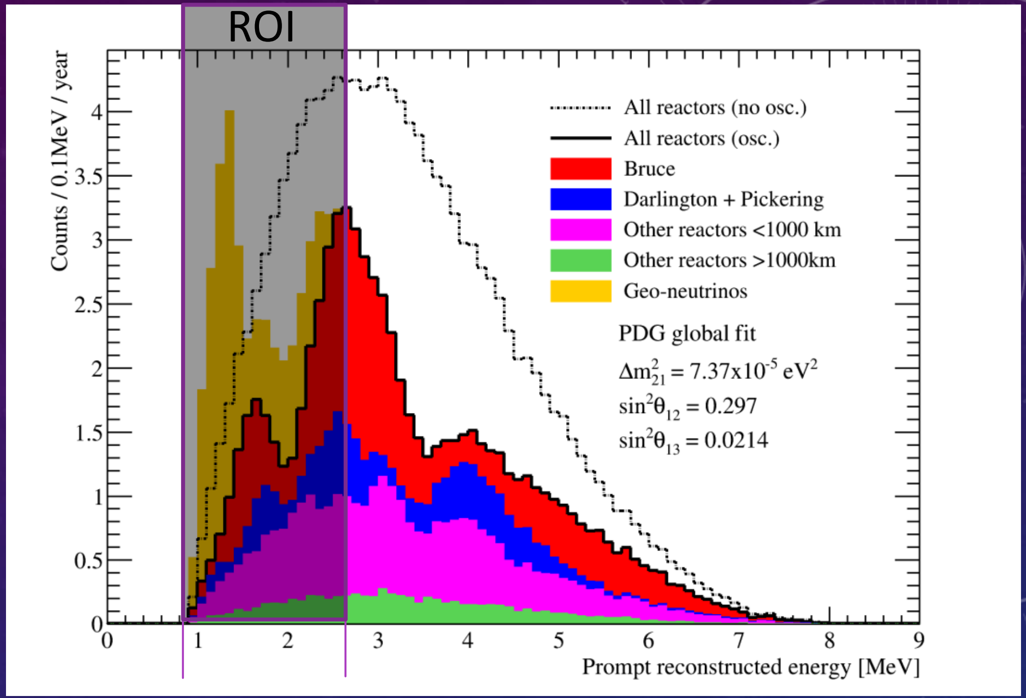
Figure adapted from Dr Valentina Lozza's "(α,n) events in SNO+" talk [(α,n) yield in low backgrounds conference, 21-22 /11/19]

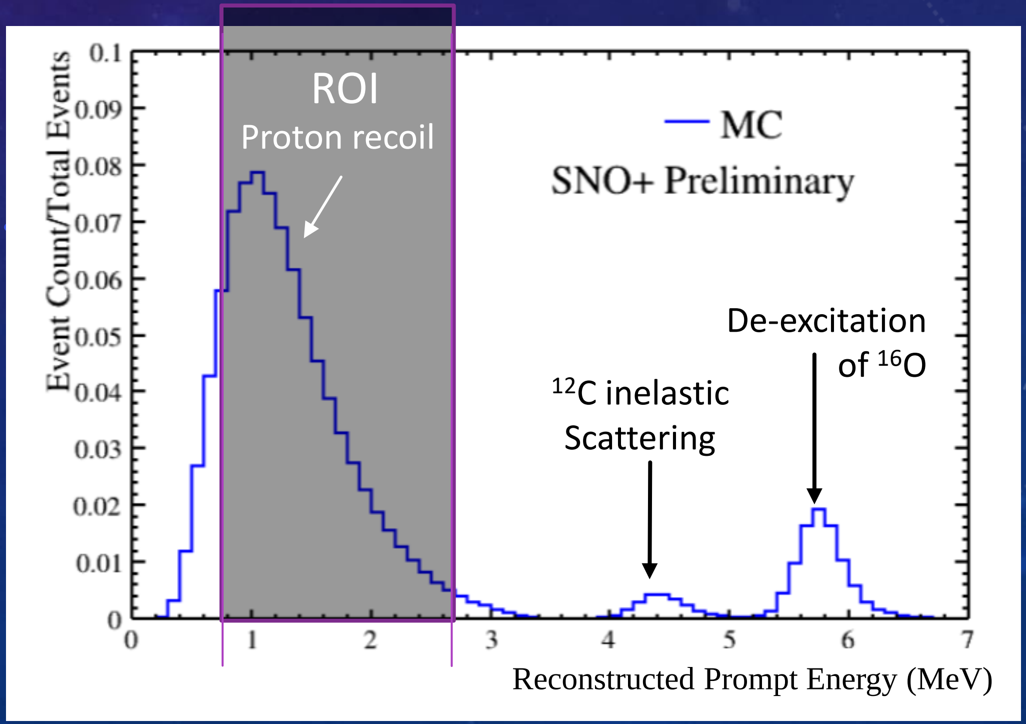
EXPECTATION COINCIDENCE SIGNALS

Identified Coincidences have 3 potential sources:

Event Type	Event Sub-Type	Events After Cuts
(α,n)	Bulk	16.0
	Surface	0.7
Antineutrino	Geo	1.1
	Reactor	2.7
Accidental / Background	Events from Sideband Analysis	0.5 (1ms window)
Totals Expected Events		***21***
Totals Observed Events		***23***

- FV cut applied at Radius = 5.8m to suppress Surface events
  - Region 10cm above Water-LAB interface also excluded
- (α,n) study subject to blinding on Prompt energy signals > 2.75 MeV
  - Blinding imposed on Reactor Antineutrinos
- Good agreement between observed and expected events
  - Corroborates measured ^{210}Po rate (R_{Po210})



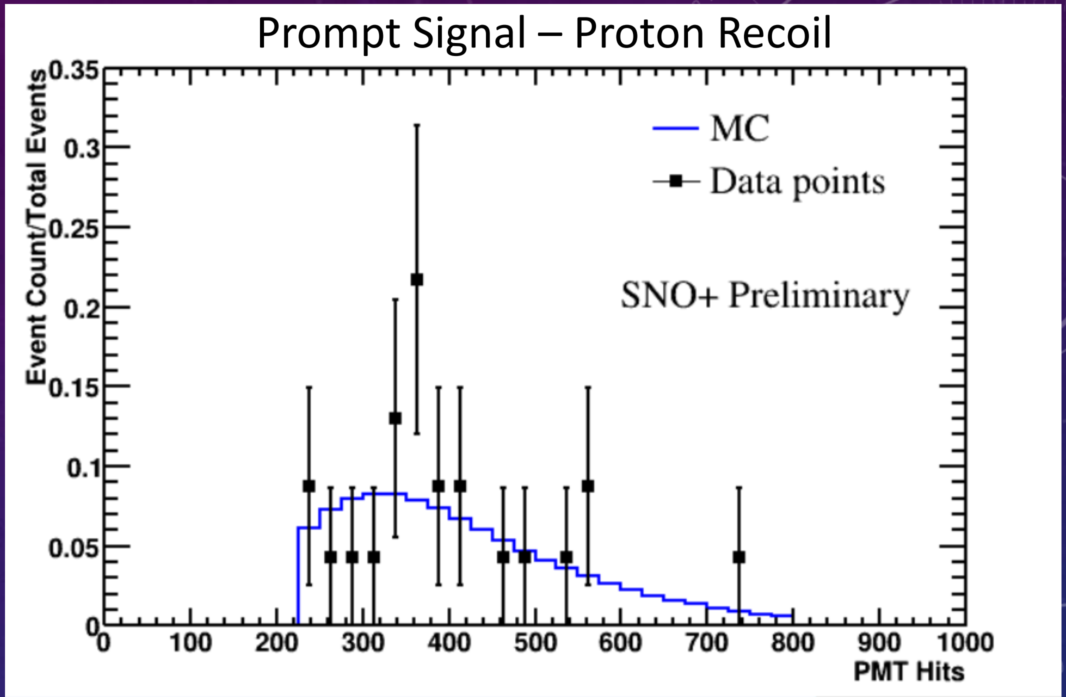


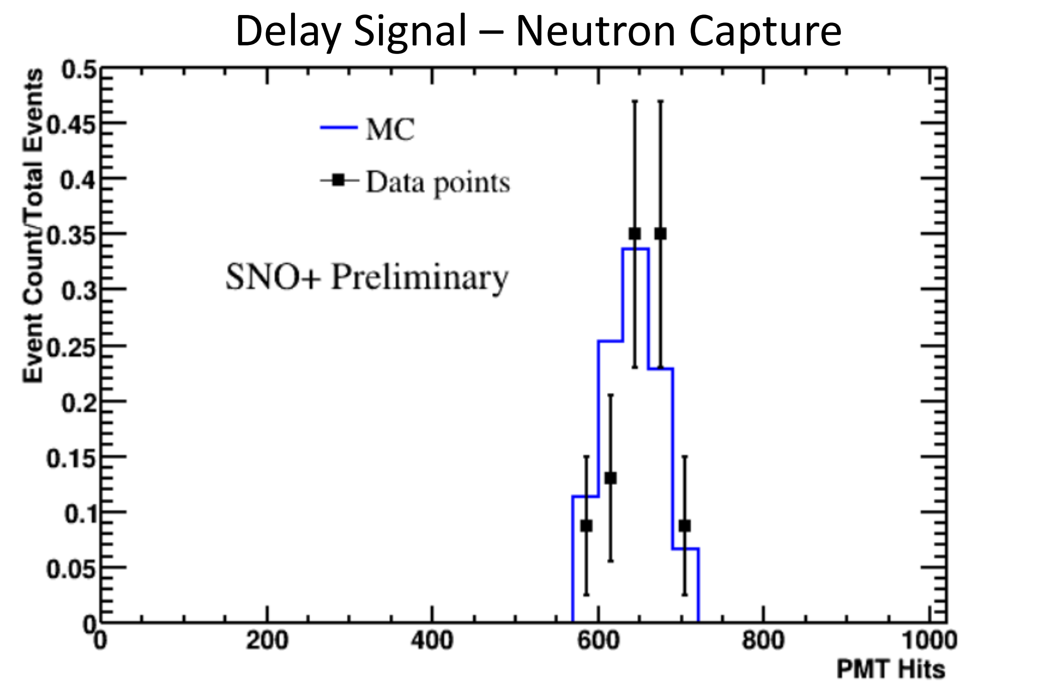
OBSERVED EVENTS: PMT HITS/ENERGY

- PMT hits used as a proxy for energy
  - Scintillator light yield ~300 PMT hits/MeV

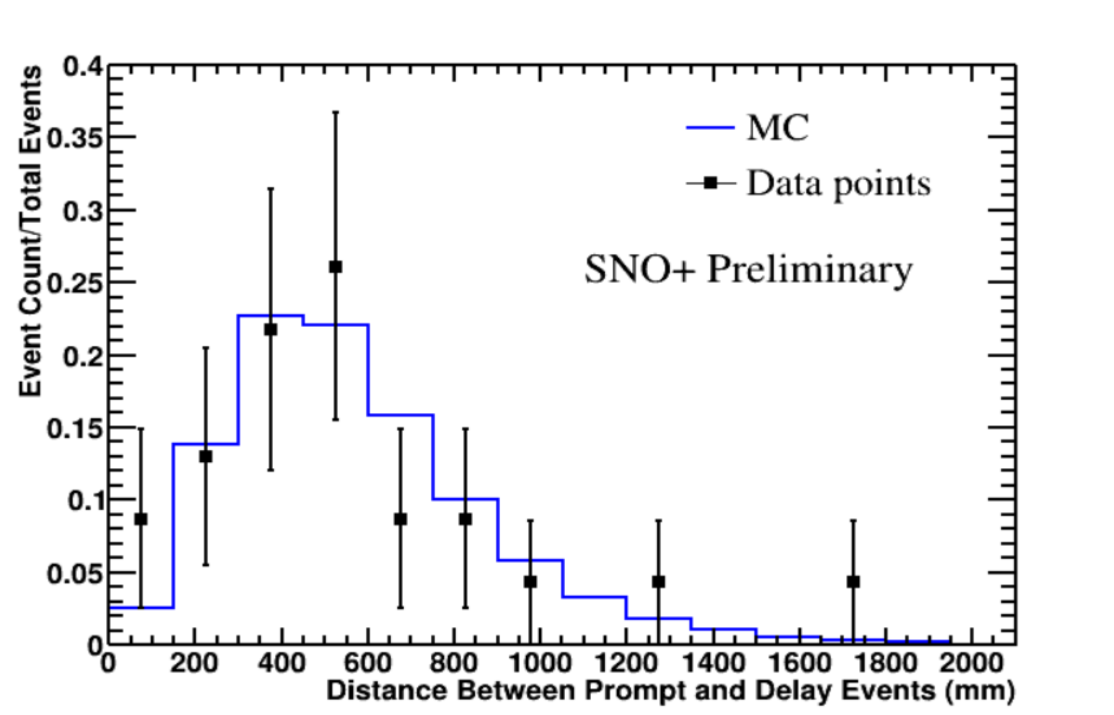
- Imposed PMT hit (*Energy*) cuts:
  - Prompt Signal: 225 - 800 hits (*0.75 – 2.65 MeV*)
    - Proton Recoil Signal
  - Delay Signal: 575 - 725 hits (*1.9 – 2.4 MeV*)
    - Characteristic 2.2 MeV neutron capture signal

- Data and MC for are compatible for both Prompt and Delay signals
  - Low statistics for Data

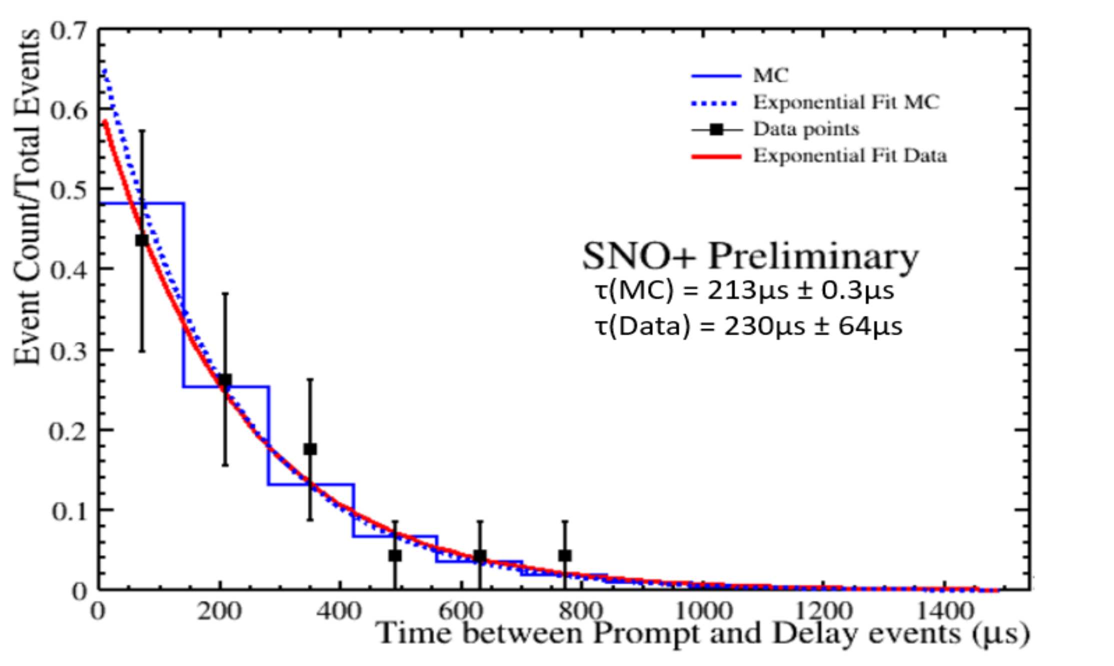




OBSERVED EVENTS (INTER-SIGNAL CUTS)



- Distance cut between Prompt and Delay signals < 2m
- Time between prompt and delayed events (Δt cut): 400ns – 1.1ms
- Good agreement between MC and Data



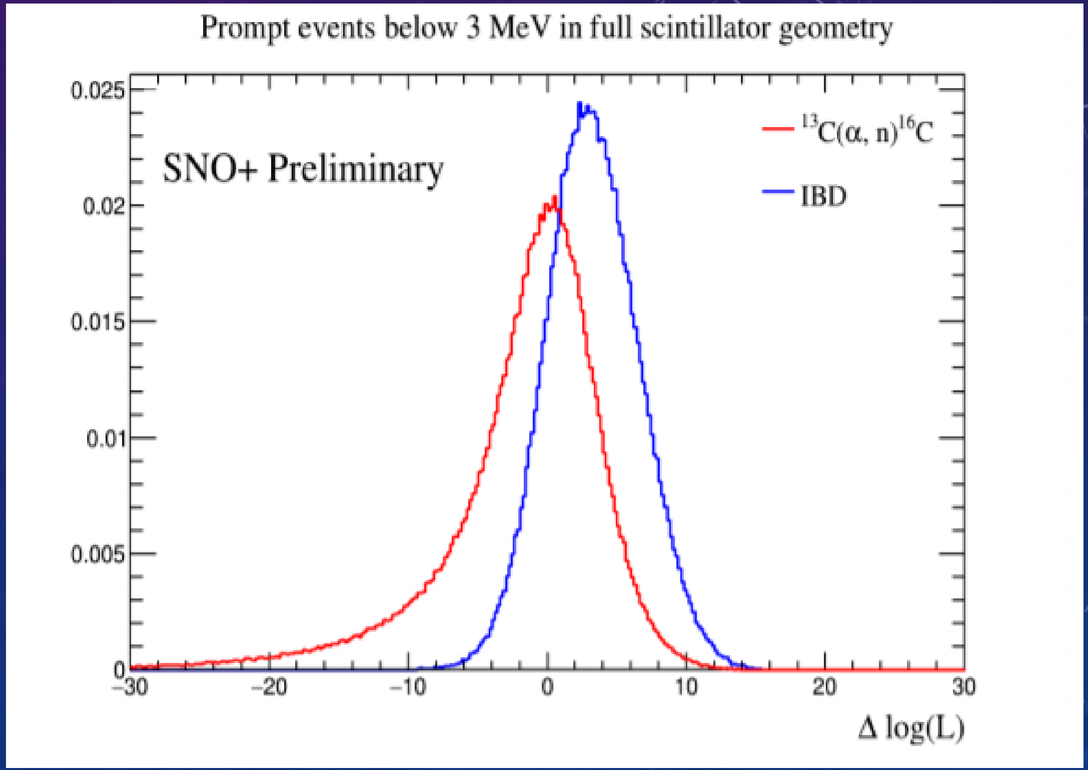
FUTURE DIRECTION OF (α,n) STUDIES

- Analysis of Surface (α,n) events
  - ^{210}Po activity used to derive ***thick target neutron yield ($A_{\alpha,n}$)***
  - Develop method to discriminate between (α,n) reactions
- Discrimination method between (α,n) and Antineutrino coincidences
  - Examine PMT hit-time residuals of known (α,n) events
  - IBD - (α,n) Classifier developed by Charlie Mills
  - Confirm (α,n) spectra in data matches MC predictions Thus, verifying classifier's accuracy
- Analysis of full scintillator data
  - Revise and apply all appropriate cuts
  - Investigate (α,n) process at higher prompt energies
  - Quantify (α,n) levels for the next data taking period

(α,n) expectation value equation

$$N^{\alpha,n}_{all} = R_{Po210} \cdot \boxed{A_{\alpha,n}} \cdot t$$

$A_{\alpha,n}$ = number of neutrons produced per alpha in a certain medium (LAB, Acrylic, etc.)



MC simulation of IBD and (α,n) *hit-time residuals*
Analysis performed by Charlie Mills

CHEERS YOU FOR YOUR ATTENTION!

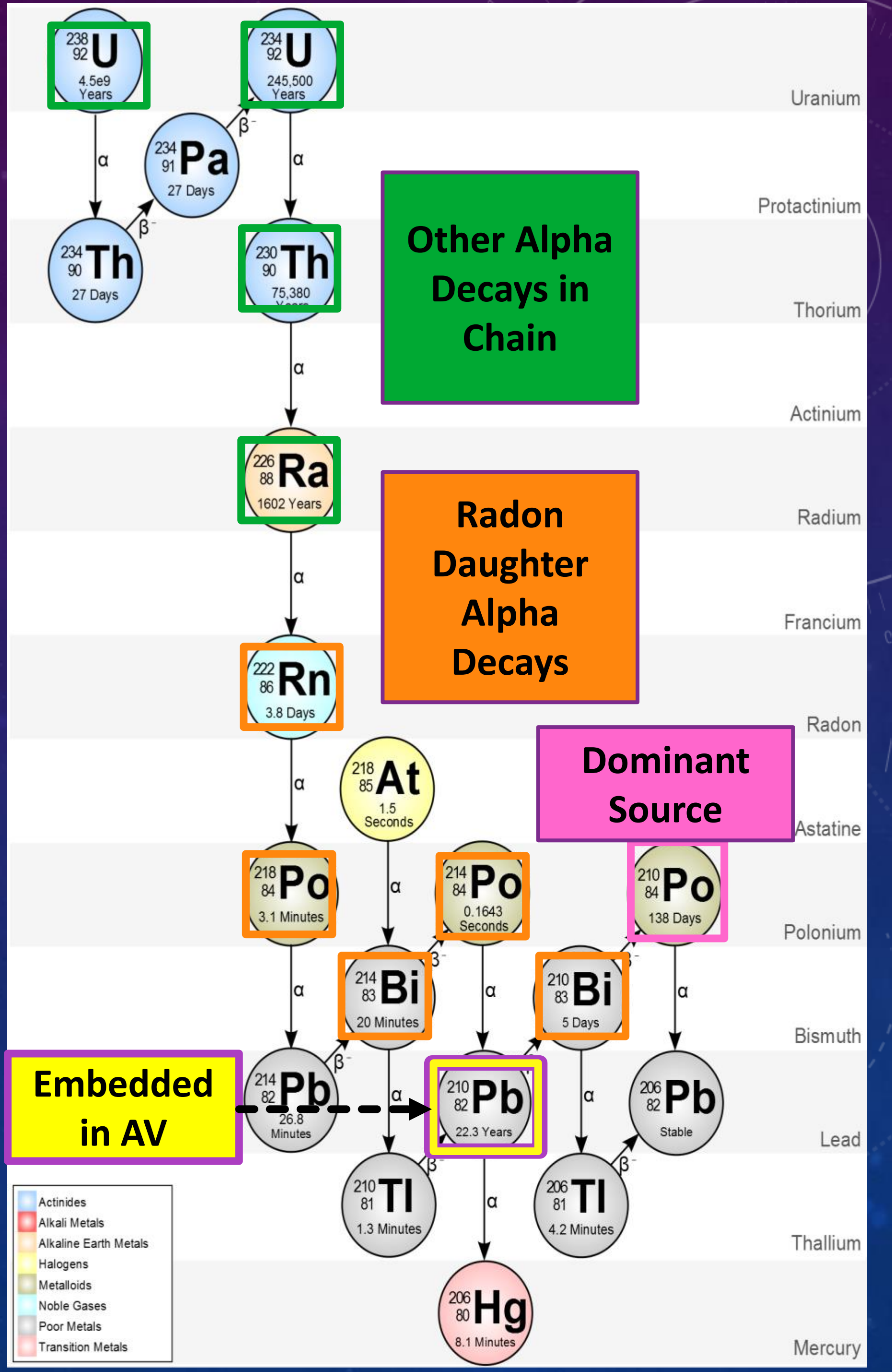
SUMMARY

- (α,n) Background:
  - (α,n) process is a major background for antineutrino studies (mimics coincidence signal of Inverse Beta Decay)
- Observations for Data Taking Period:
  - 23 observed coincidences in agreement with 21 expected events
  - Good agreement between MC and Data spectra
- Future Direction:
  - Develop analysis of (α,n) AV Surface events
    - Separate different (α,n) reactions
    - Verify thick neutron yield value using ^{210}Po Surface activity
  - Investigate (α,n) event hit time residuals -> Confirm MCs match events in data & corroborate classifier's accuracy
  - Tailor current (α,n) Bulk [and later Surface] analysis for application to the full detector

BACKUP SLIDES

(α,n) SOURCES

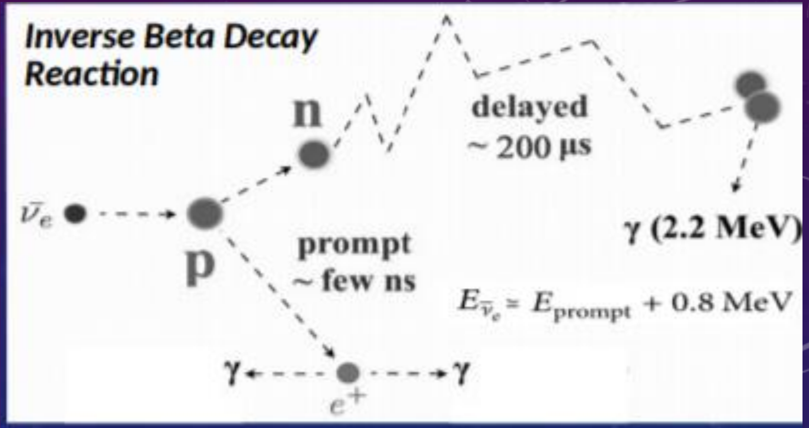
- All α-decays in the detector contribute to (α,n) background
- ***Radon Daughters*** are a prominent source of alphas in LAB (if secular equilibrium is not maintained)
- Alpha sources:
  - Intrinsic scintillator purity and introduction of Rn and Po during filling operations
    - ^{210}***Po*** is the dominant α source
  - Radon ingress - *minimised but not fully eliminated*
  - Leaching of ***Radon daughters*** plated on the AV's surface throughout AV's lifetime – particularly ^{210}***Pb***

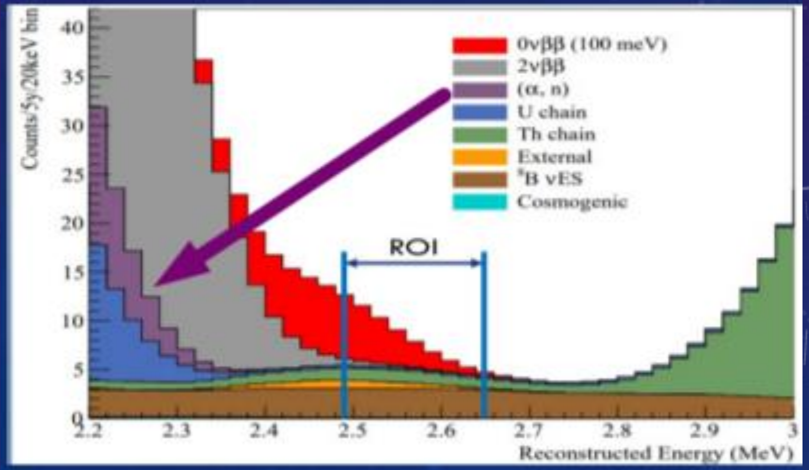


(α,n) AS A BACKGROUND

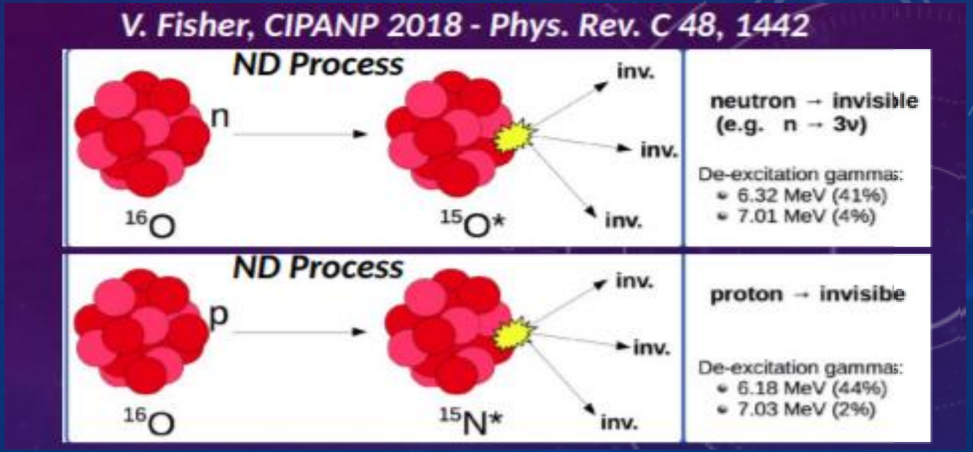
(α,n) reactions act as a background for multiple SNO+ studies:

- **Antineutrino analysis -**
  - Reactor and geoneutrinos produce Inverse Beta Decay (IBD) signals
  - (α,n) mimics IBD coincidence signals
- Neutrinoless double beta decay analysis -
  - Proton recoil and neutron capture signals can individually fall within the ROI for 0νββ
- Invisible Nucleon Decay (ND) analysis -
  - High energy gammas from ^{16}O de-excitation can fall into Regions of Interest (ROI) for $^{15}O^*$ and $^{15}N^*$decay modes





*Predicted neutrinoless double beta decay and background signals**
**AlphaN rejection already applied to plot*

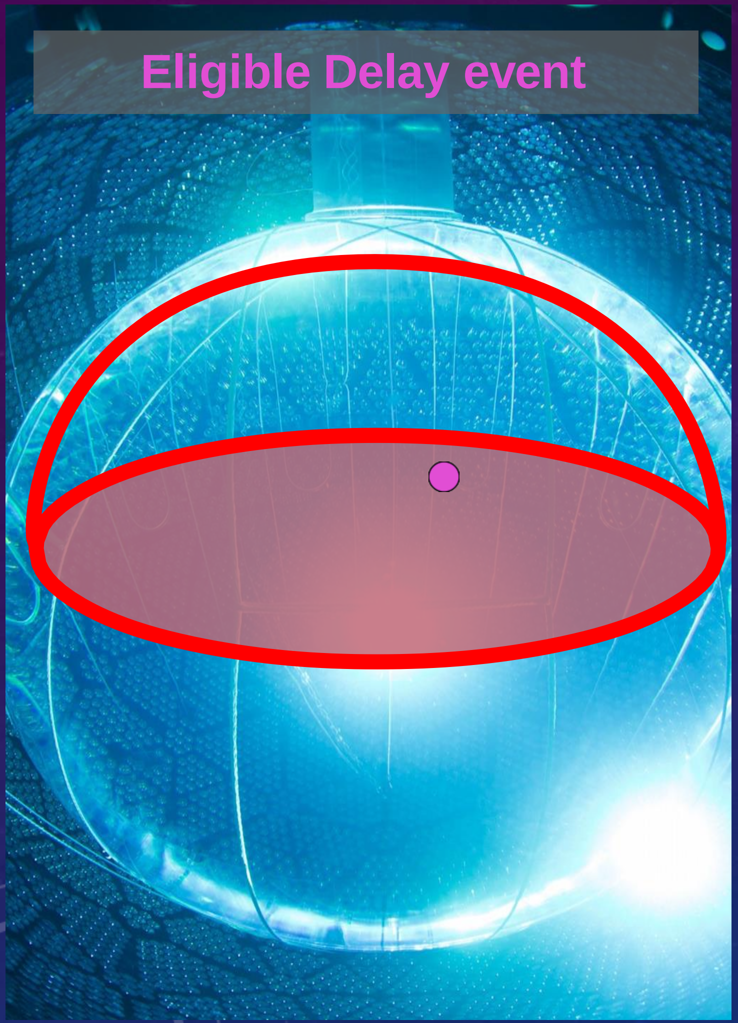


(α,n) COINCIDENCE IDENTIFICATION TECHNIQUE

Delay Event

Fiducial volume cut

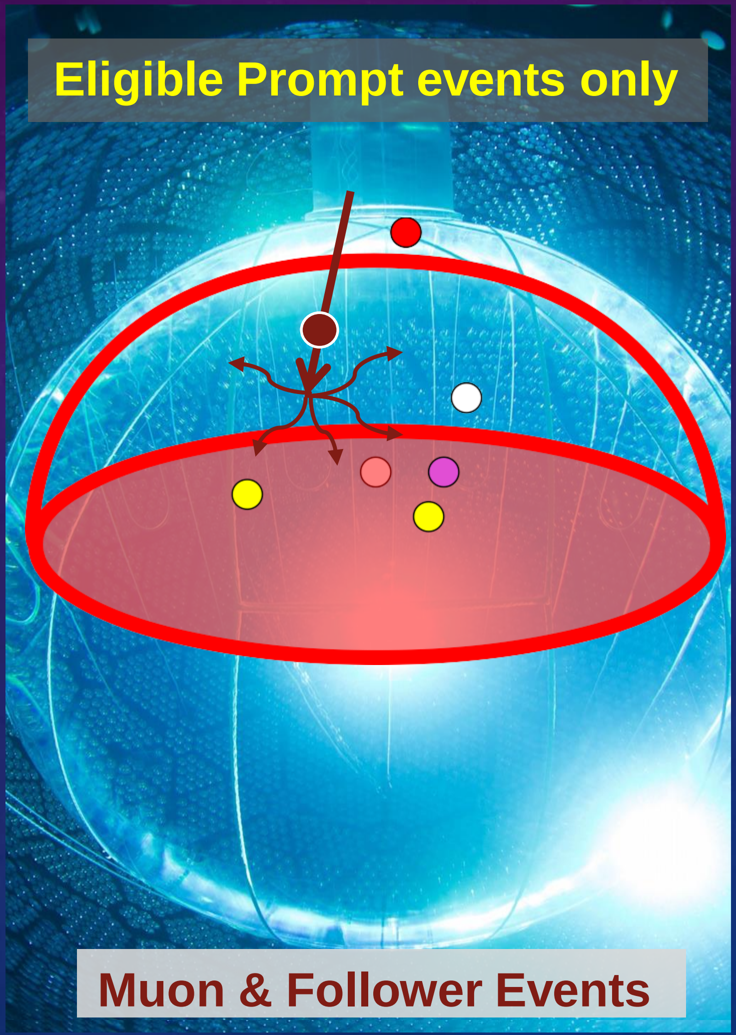
Energy cut



Prompt Event

Fiducial volume cut

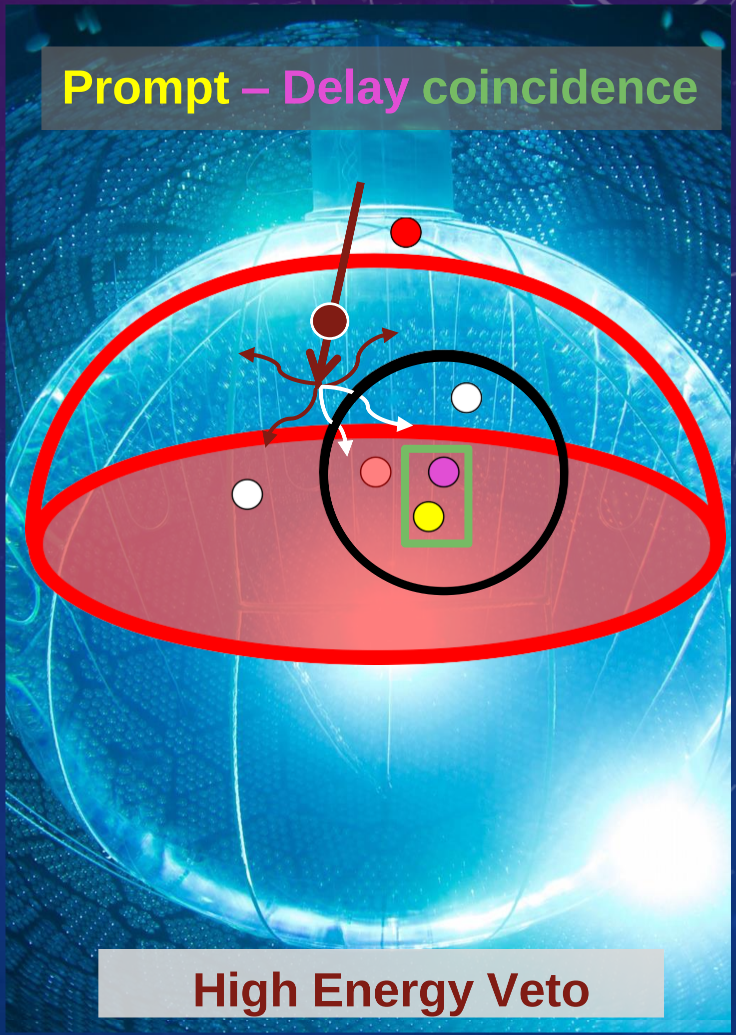
Energy cut



Coincidence

Radial distance cut

Timing window cut



COINCIDENCE EXPECTATION VALUES - (α,n) Contribution

True (α,n) Event Contribution:

$$N_{all}^{\alpha,n} = R_{Po210} \cdot A_{\alpha,n} \cdot t$$

- ^{210}Po rate measured
- (α,n) contributions from detector Bulk and from AV surface
- FV cut applied to suppress Surface events
  - Radius = 5.8m & Z = 0.85m
- Expectation value scaled by cut efficiency

Variable	Definition	Value
R_{Po210}	Bulk ^{210}Po Rate	100 Bq
$A_{\alpha,n}$	Thick Target Neutron Yield in Medium (^{13}C in LAB)	6.11x10^{-8} neutrons per alpha particle
t	Data Taking Period	1644 hours (68.5 days)
$N_{all}^{\alpha,n}$	Bulk (α,n) Expectation Value	36

(α,n) Event Parameters

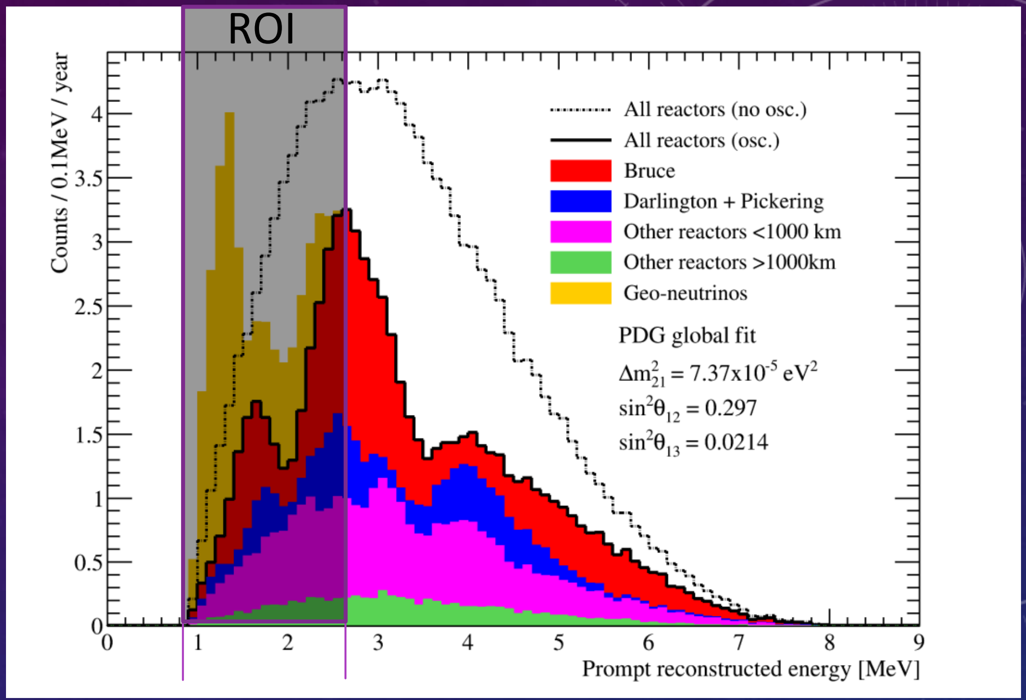
COINCIDENCE EXPECTATION VALUES - ANTINEUTRINOS

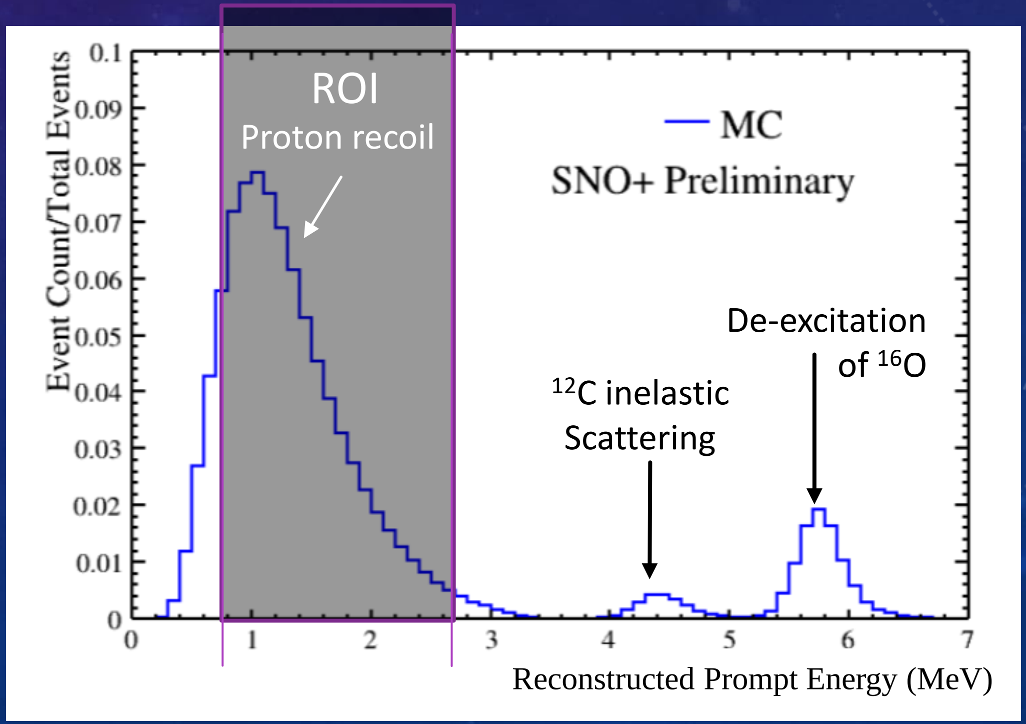
Antineutrino Signals:

- Expectation values for full detector over one year period:
  - Geoneutrinos = 25.2
  - Reactor neutrinos = 158.4

- Values scaled for data taking period and partial fill LAB volume

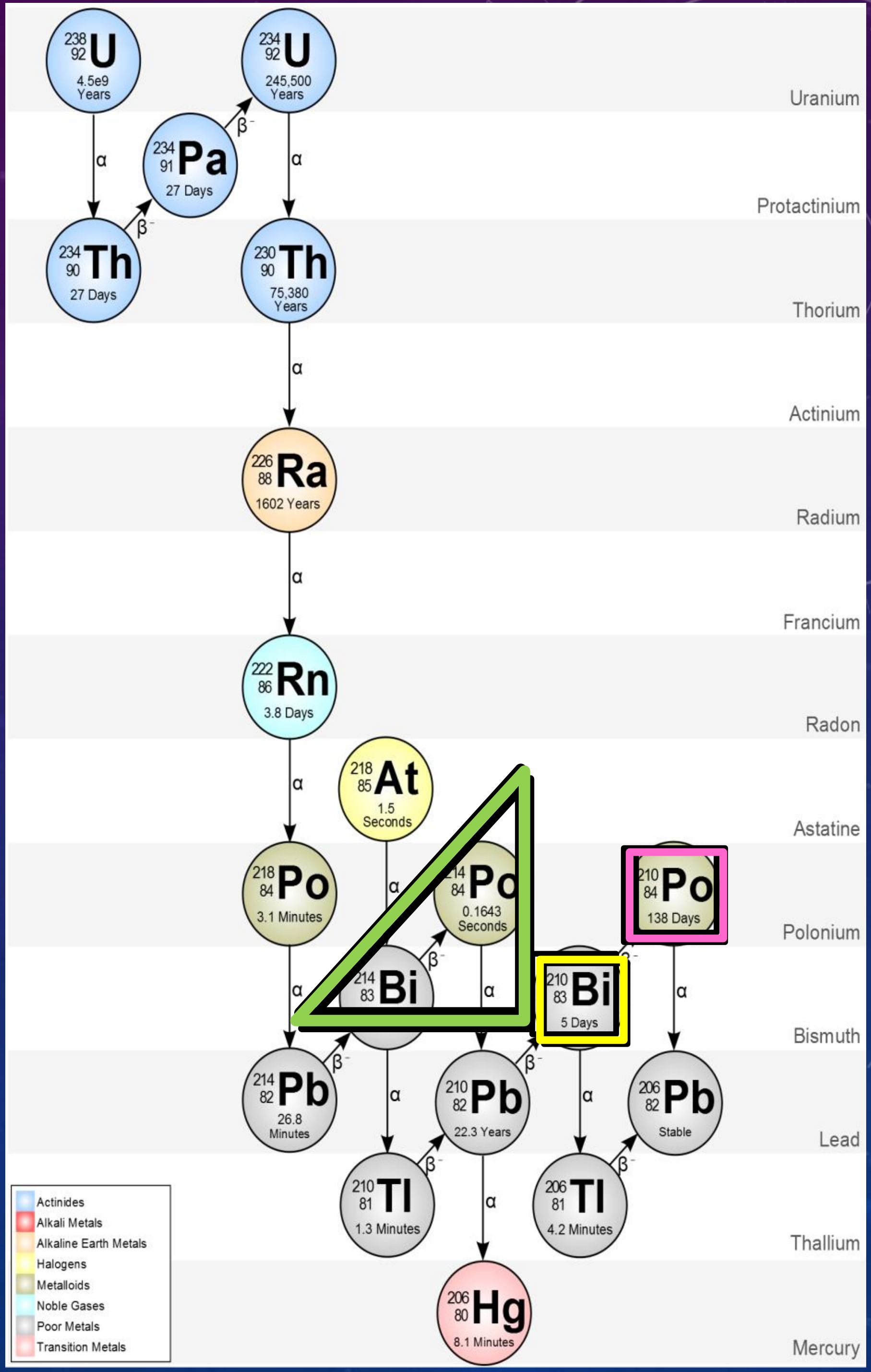
- Analysed period subject to blinding for Reactor antineutrinos
  - Limits current (α,n) analysis to proton recoil signals only





COINCIDENCE EXPECTATION VALUES - BACKGROUND/ACCIDENTALS

- ***^{210}Po singles***, ***^{210}Bi singles*** and ***^{214}Bi-^{214}Po coincidences***
- Rate of accidental (background) events determined by sideband analysis
- Sideband Analysis: analysis of ROI where no (α,n) events are expected
  - Sideband Δt range: 1.1ms – 5.1ms
- Largest source of uncertainty



FULL BREAKDOWN OF EXPECTATION AND EFFICIENCY VALUES

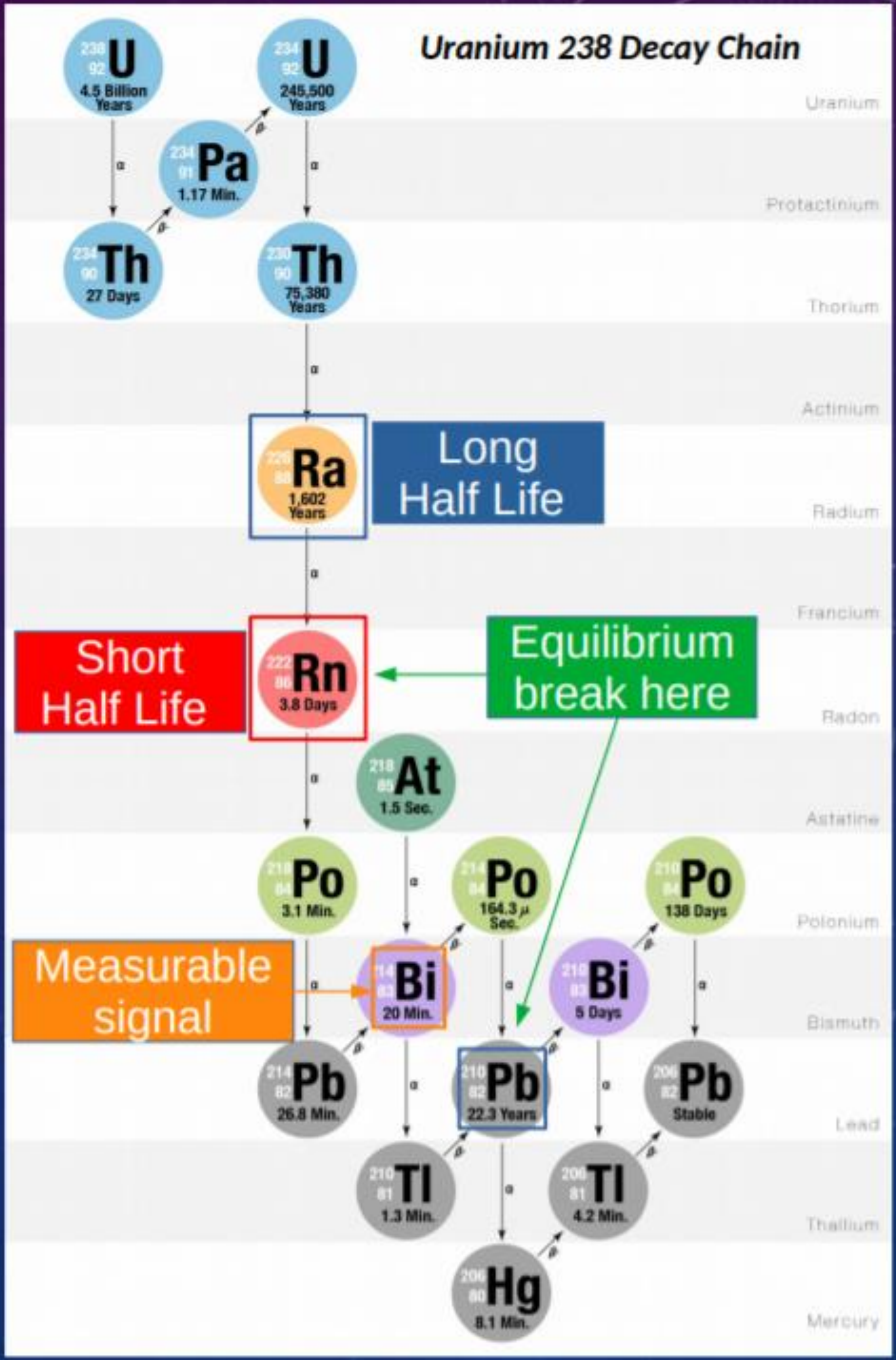
Event Type	Event Sub-Type	Expectation Values (for 68.5 days)	Cut Efficiency (%)	Events After Cuts
(α,n)	Bulk	36.2	44.3	16.0
	Surface	452.1	Supressed*	0.7
Antineutrino	Geo	1.9	58.6	1.1
	Reactor	12.1	22.4	2.7
Accidental / Background	Events in Full Sideband Analysis	2 (4ms window)	-	0.5 (1ms window)
Totals Expected Events				***21***
Totals Observed Events				***23***

**Surface (α,n) has individual cut efficiencies for C and O isotopes in different media (Acrylic, LAB, etc.) All efficiencies of the order of 0.01 – 0.1% and are therefore displayed as suppressed*

WATER ANALYSIS BACK-UP SLIDES

RADON ANALYSIS CONTEXT

- Natural Radon gas present in mine air (130 Bq/m^3 at SNOLAB)
- Ingress breaks the secular equilibrium of Thorium 232 & Uranium 238 decay chains (^{238}U is more significant)
- Radon 222's daughters are a background for Nucleon Decay and Solar Neutrino studies
  - ➢ Cherenkov detectors not sensitive to α radiation
  - ➢ Beta radiation of Bismuth 214 is a dominant background
- Bismuth 214 used as a proxy to calculate Radon levels in detector
- Previous day-by-day monitoring carried out essentially in real-time (during water phase)
  - ➢ Detector data reprocessed using more accurate detector conditions. Analysis performed on this data



BISMUTH 214 ANALYSIS TECHNIQUE

- Analysis performed using an algorithm to determine Bismuth 214 event density rates
- Performed for 3 Fiducial Volumes (FVs)
- Individual analysis performed of spherical, hemispherical and segmented regions
- Data compared to MC simulations to derive gram for gram comparisons of ^{238}U to H_2O

Algorithm Analysis

Data cleaning cuts applied:
exclude instrumental noises

↓

Energy and position values used to reconstruct events

↓

Isotropy cut applied:
Cherenkov signal is anisotropic

↓

ITR cuts applied:
Exclude events with broad timing distributions

↓

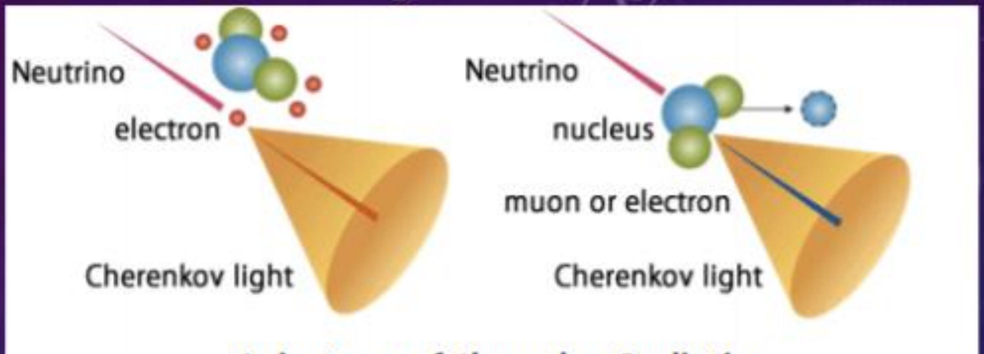
Energy cuts applied:
Exclude events below 3.5 MeV

↓

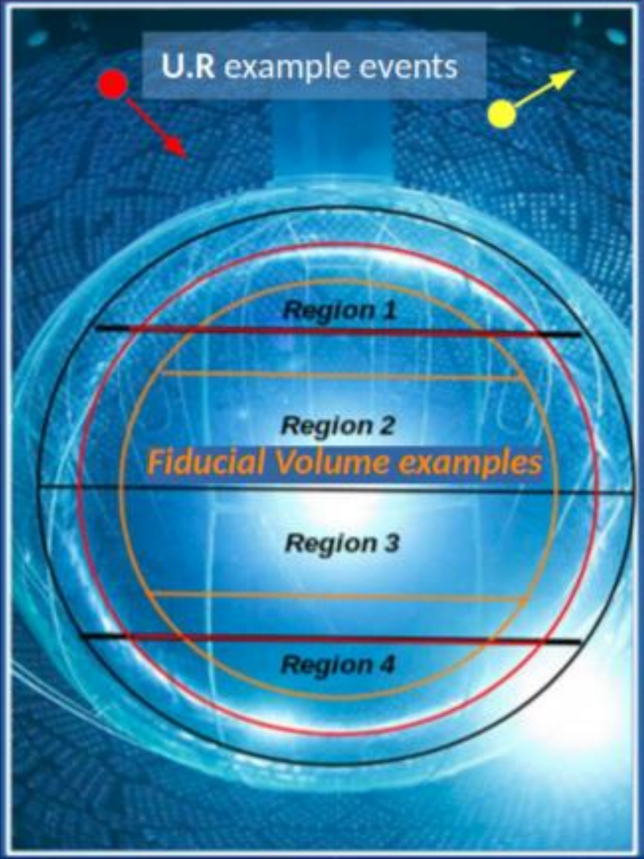
Fiducial Volume cuts applied:
Reduce backgrounds from regions other than analysed volume

↓

U.R cuts applied:
[External data only]
Red Rejected, Yellow Accepted



Anisotropy of Cherenkov Radiation



Radii of Spherical FVs used:

5.5 m
5.0 m
4.3 m

BISMUTH 214 REANALYSIS RESULTS

Redacted

- Comparisons drawn between average values and spectral shapes
  - Any discrepancies investigated and explained → Reprocessed average purity approx. x2 better

For reprocessed data:

- Event reconstruction improved for external events
- Internal reconstruction more uniform across detector
- Energy calibration factor potentially required

↓

Spectral shapes agree well
(Small discrepancies due to binning)