Searching for neutrino absorption in ^{40}Ar using the DEAP-3600 dark matter detector

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on behalf of the DEAP neutrino analysis group

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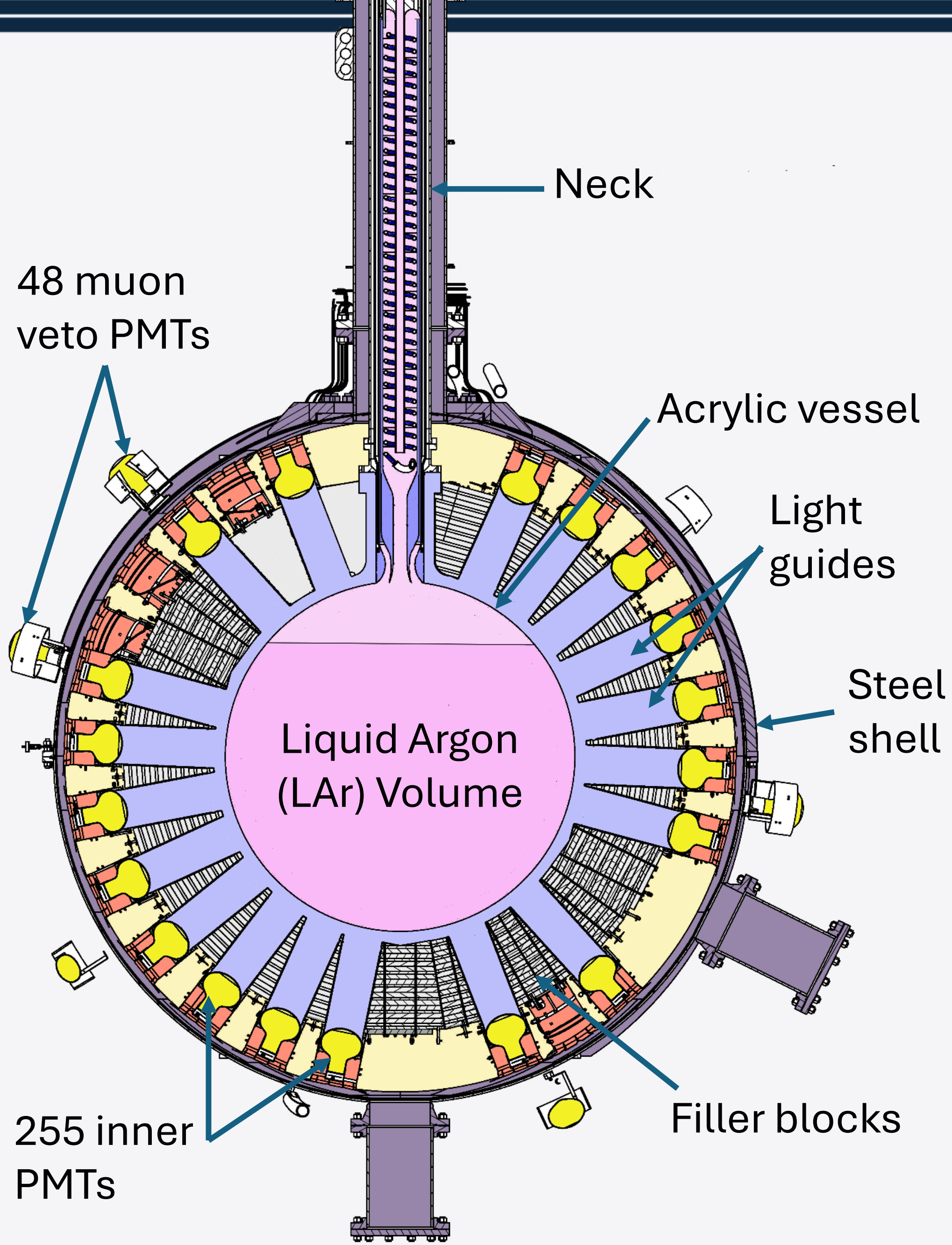
DEAP-3600

- **D**ark matter **E**xperiment using **A**rgon **P**ulse shape discrimination
- Single-phase dark matter direct detection experiment at SNOLAB.
- In addition to the WIMP search there are other studies using DEAP data

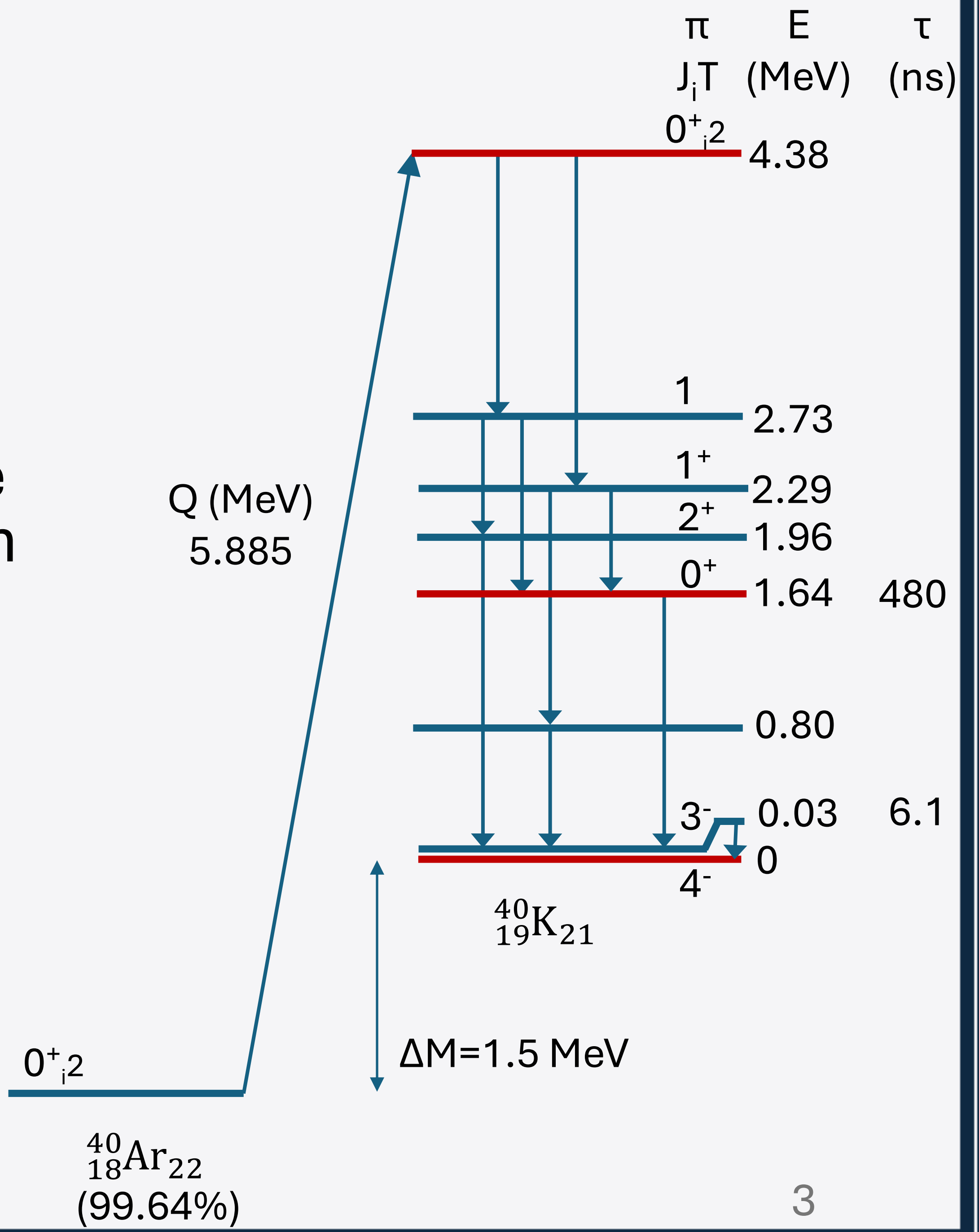


Neutrino Absorption

- Initial paper by R. S. Raghavan (1986) proposed that low energy neutrino interactions could be observed via the super-allowed $0^+ \rightarrow 0^+$ Fermi transition from the ground state of ^{40}Ar to an excited state of ^{40}K.

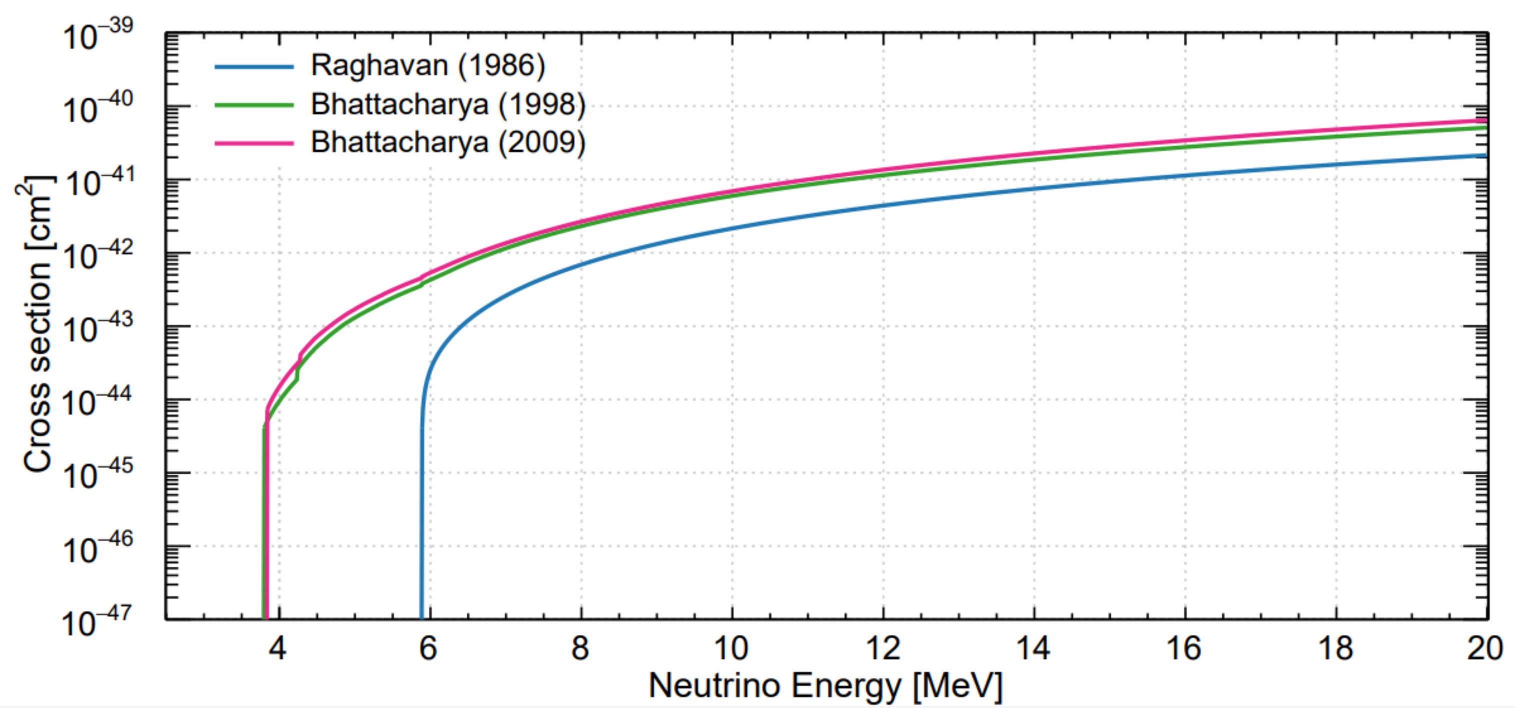
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

- This excited ^{40}K state would decay through characteristic gamma rays to the ground state.

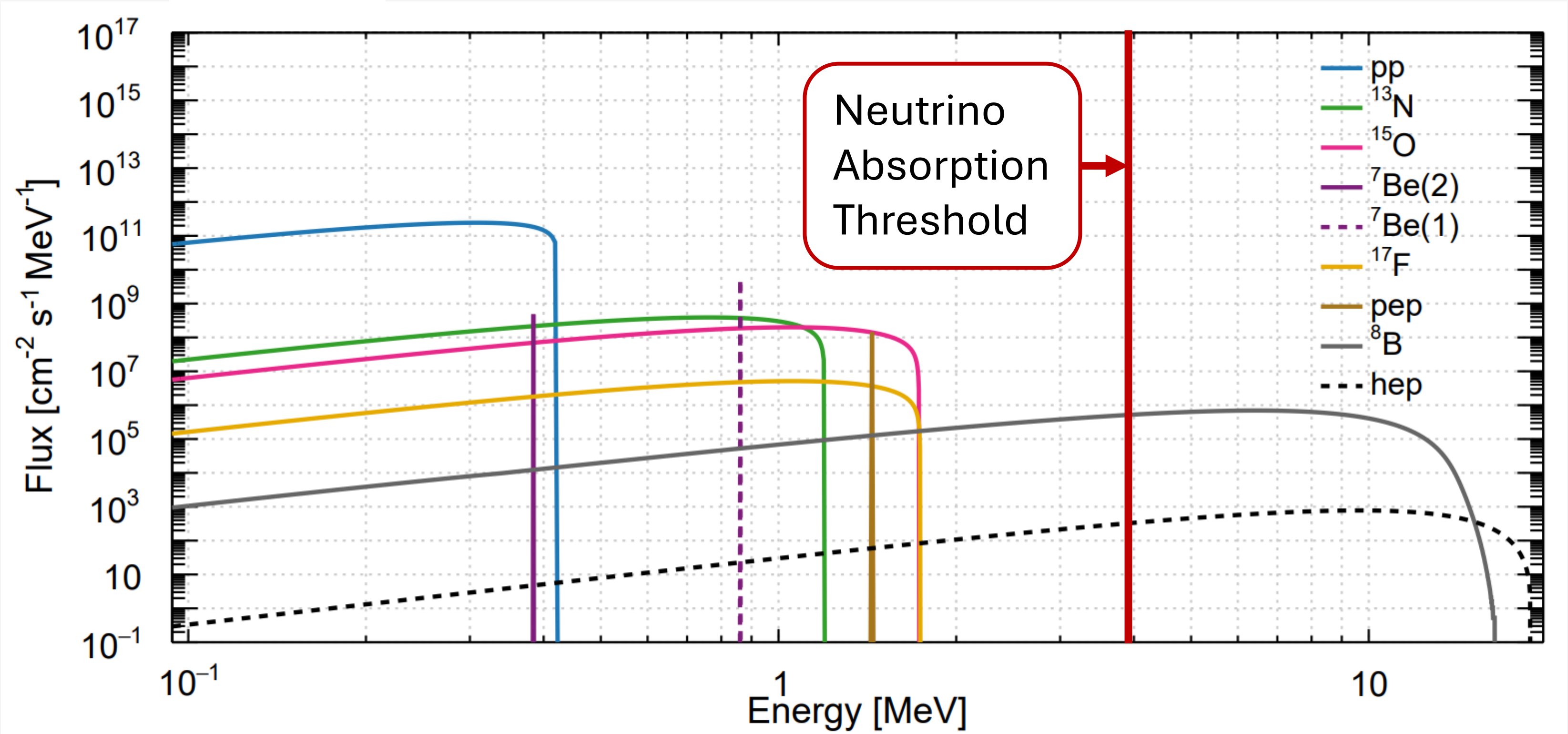


$^{40}Ar \rightarrow {}^{40}K^*$ transition

- M. Bhattacharya et al. measured Gamow-Teller (GT) strengths for transitions from ^{40}Ar to $^{40}K^*$
- Energy threshold decreased from 5.885 MeV (Fermi) to 3.9 MeV (GT)



Solar Neutrino Spectrum



Given the cross-sections and flux integrated over energy, we expect

Γ = 2.2 events/tonne-year

From SNO results we have a measurement of the ^{8}B solar neutrino integrated flux

$$\phi(\nu_e)_{SNO} = 1.76 \,^{+0.05}_{-0.05}(stat.)\,^{+0.09}_{-0.09}(sys.) \times 10^6 \, cm^{-2} s^{-1}$$

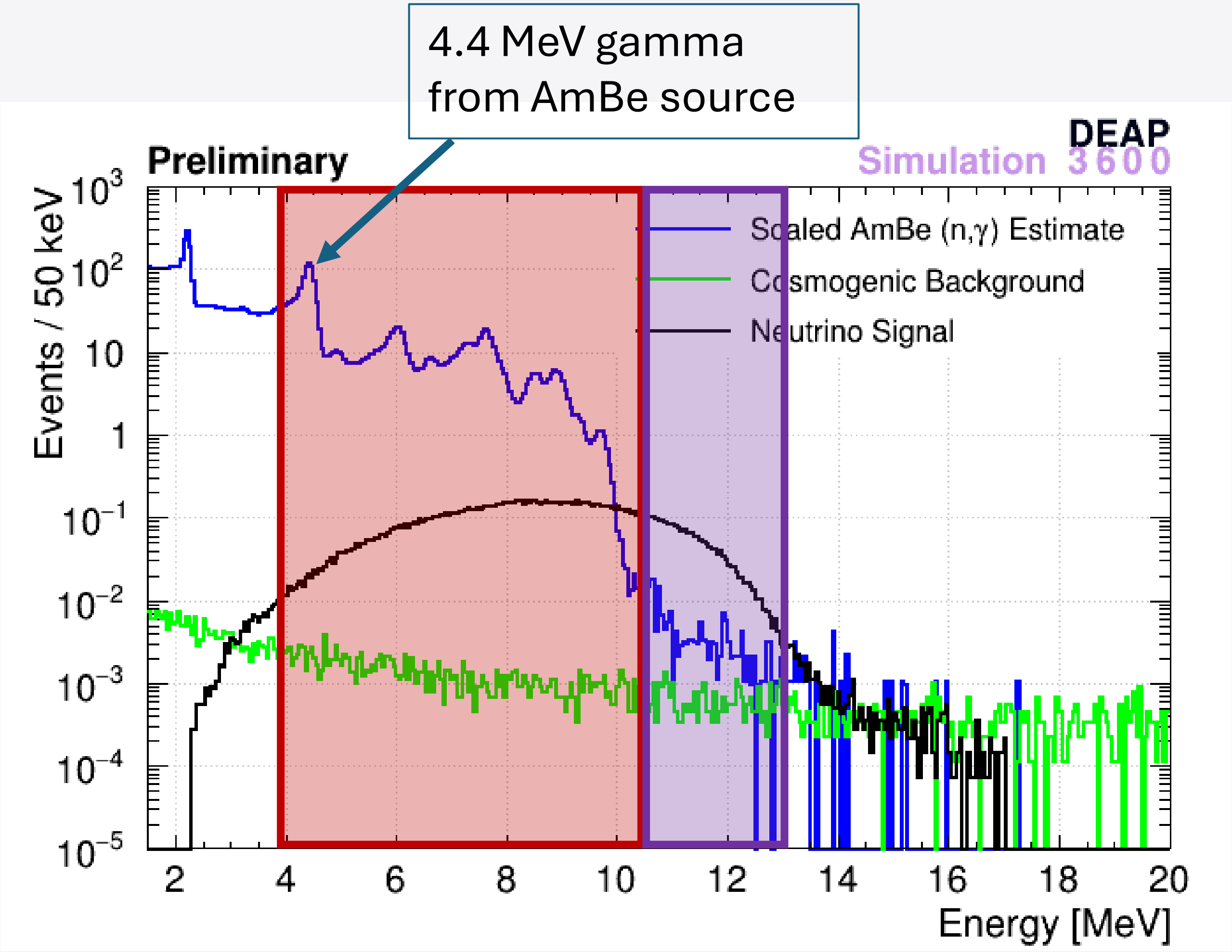
Search Regions

Delayed Coincidence

- Unique neutrino signature
- Neutrino signal << background

High-Energy Region

- Counting experiment
- Neutrino signal > background
- Accurate background model



Expected Signal

Delayed Coincidence Region

$$E_{prompt} = E_e + \sum E_\gamma$$

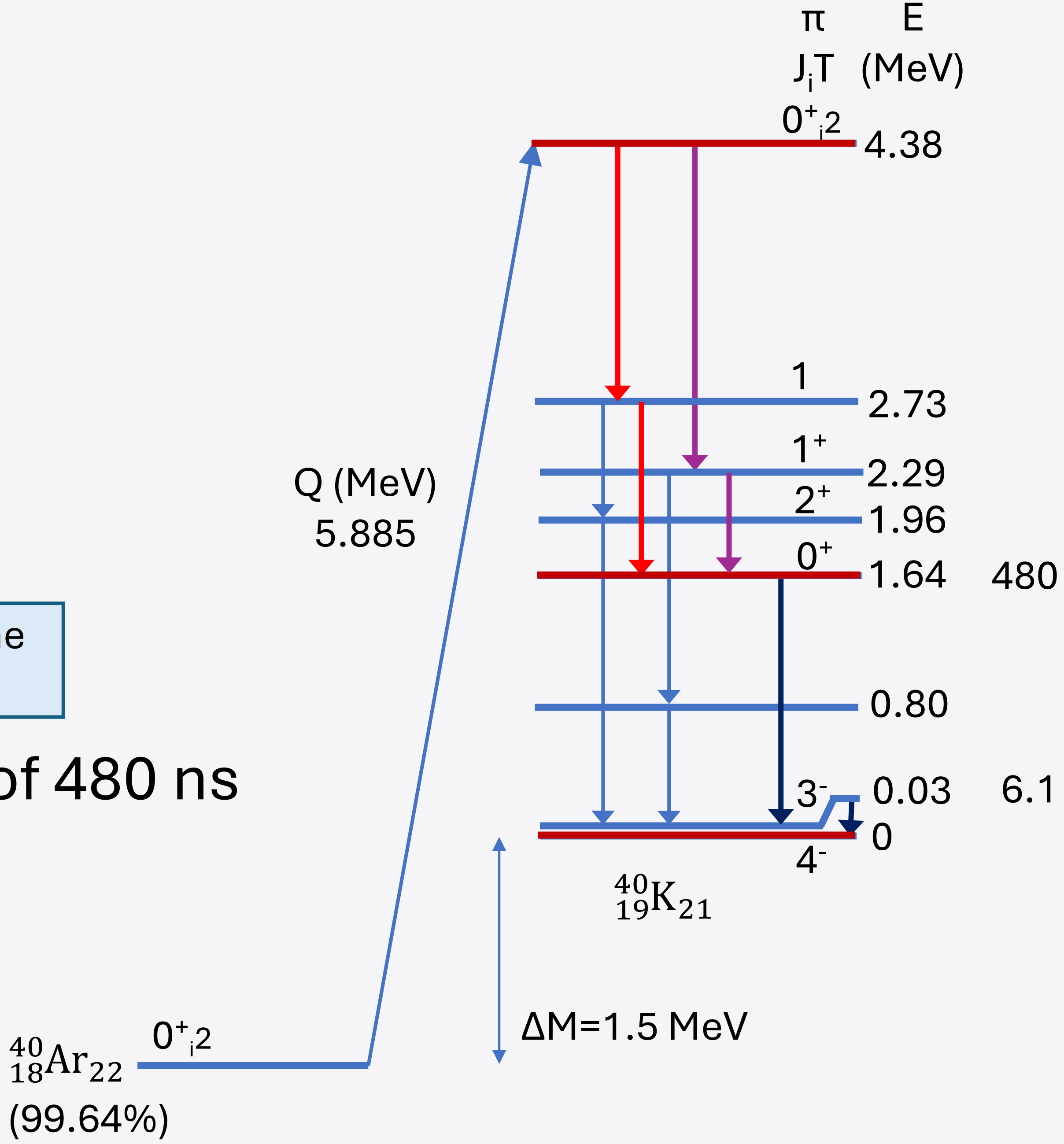
Sum of gammas until it reaches the 1.64 MeV metastable state

Metastable state has a mean lifetime of 480 ns

$$E_{delayed} = 1.64\ MeV$$

Energy of neutrino

$$E_\nu = E_{prompt} + E_{delayed} + 1.5\ MeV$$



Expected Signal

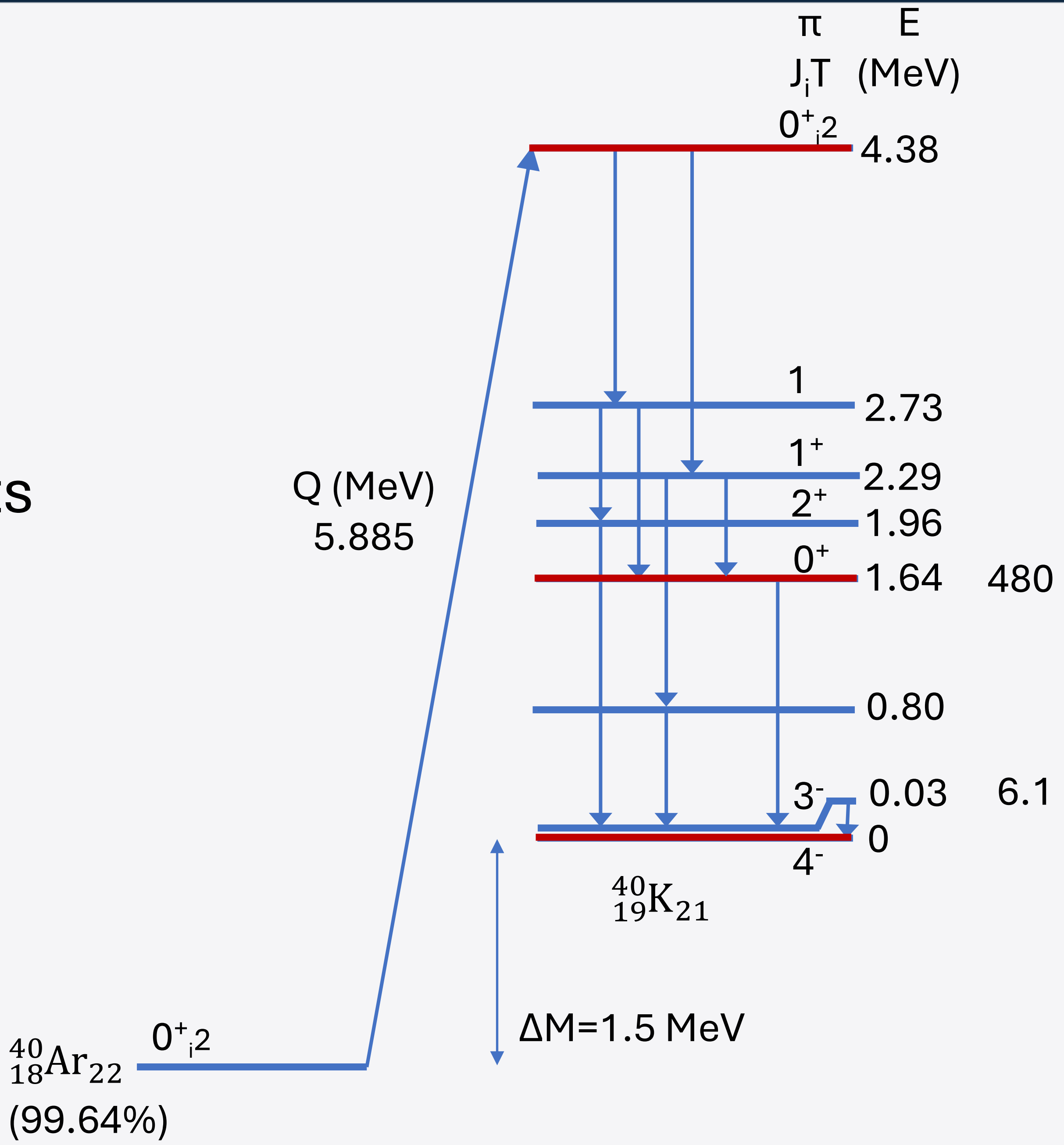
High-Energy Region

Counting excess high-energy events over expected background

$$E_\nu = E_e + \sum E_\gamma + 1.5\ MeV$$

Energy of neutrino

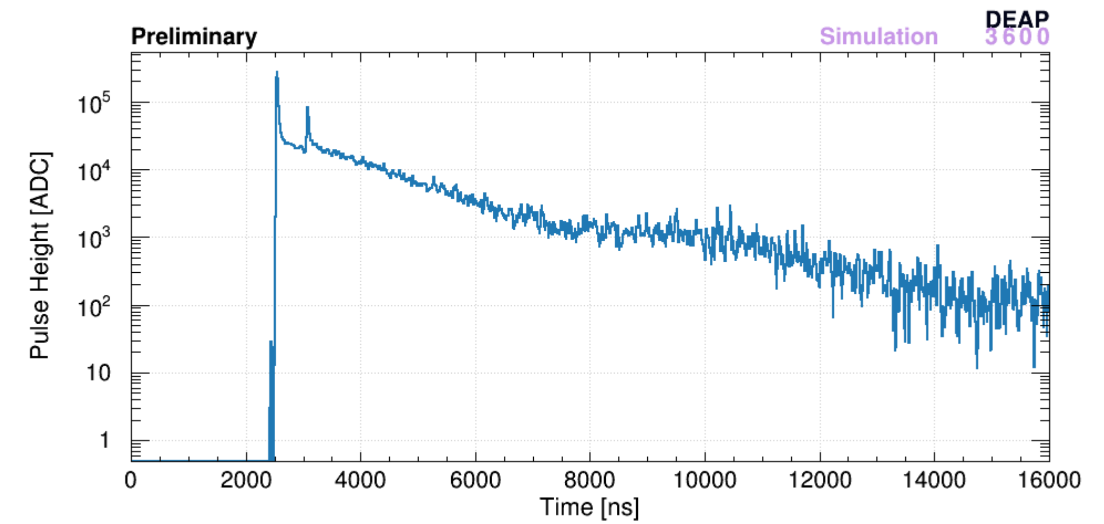
$$E_\nu = E_{obs} + 1.5\ MeV$$



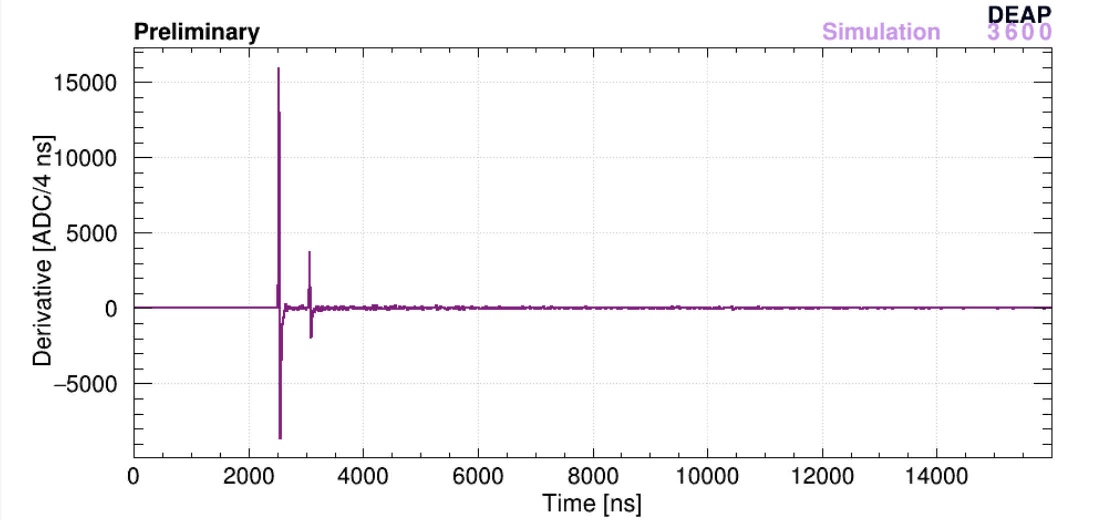
High-Energy Pile-Up Algorithm

- Identify peaks by when the waveform derivative passes a certain threshold.
- Outputs time and height of each peak among other quantities.

Waveform

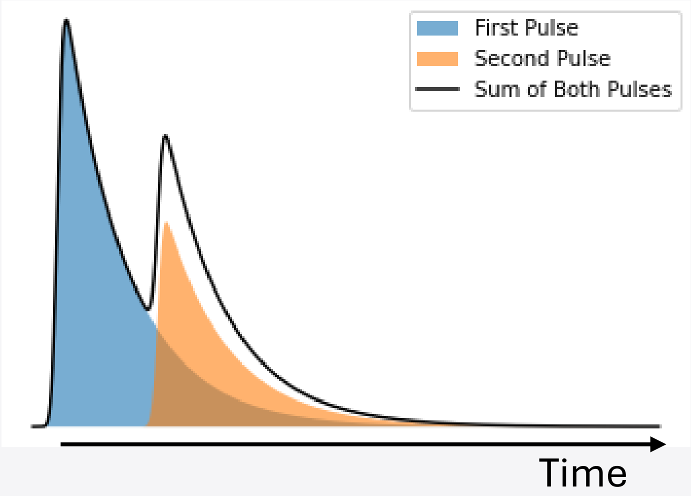


Derivative



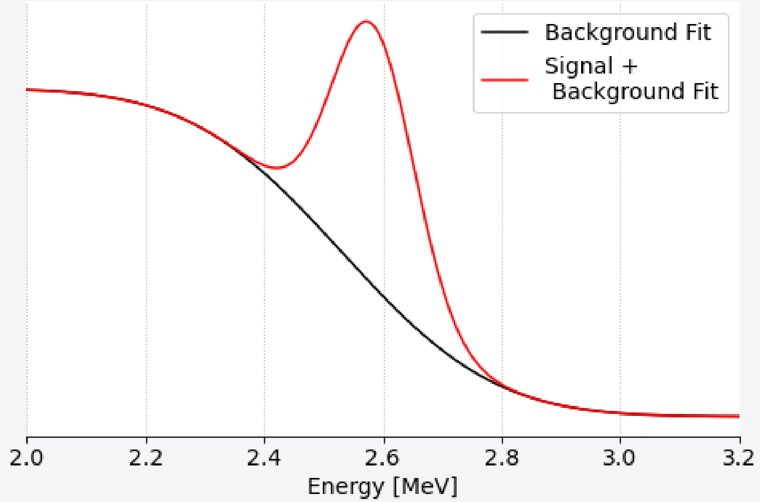
Data-Driven Delayed Coincidence Energy Model

- Use this model to identify the 1.64 MeV delayed signal
- Not trivial to find delayed energy peak because it can be affected by the prompt peak



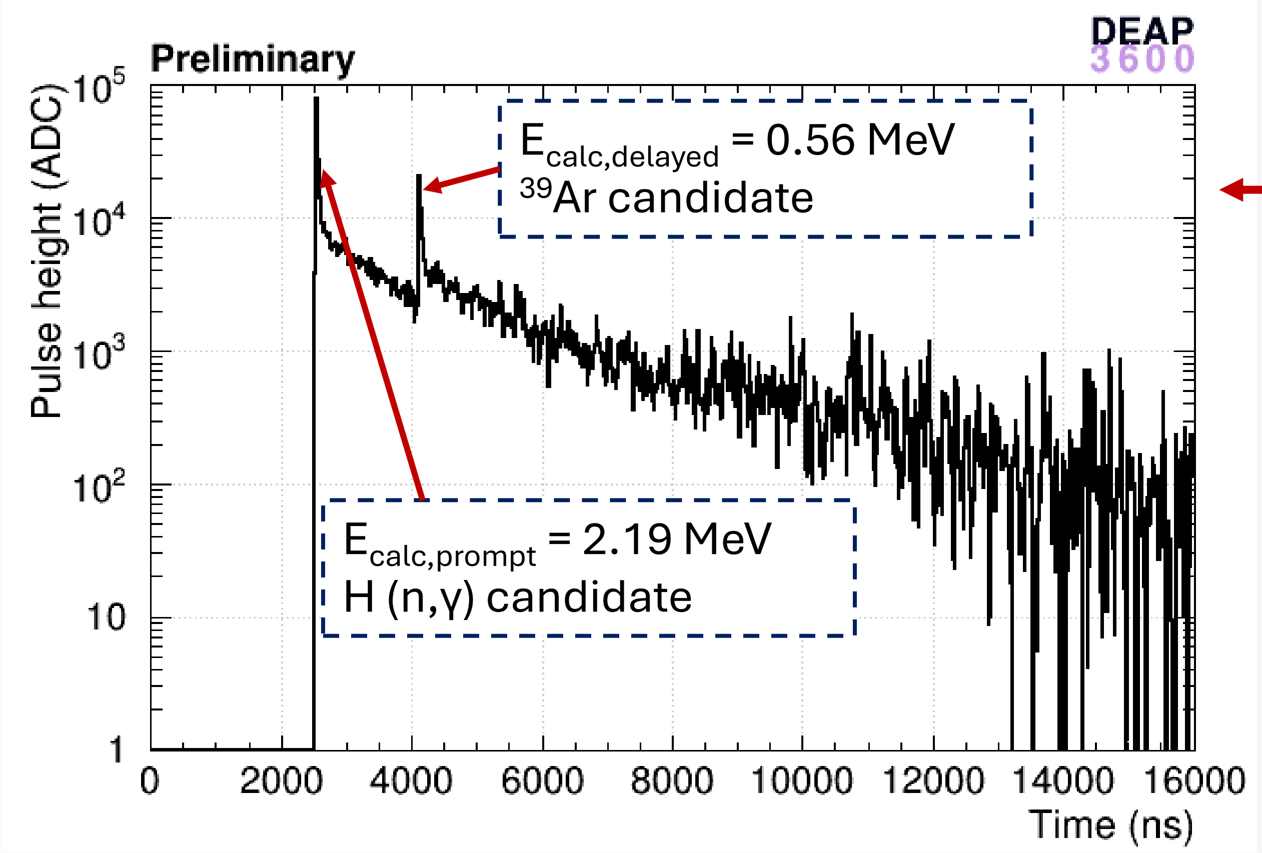
Model Procedure :

1. Fit single peak height-energy distribution →prompt energy model $E_{prompt}(ph_1)$
2. Delayed coincidence is $$E_{delayed} = E_{total} - E_{prompt}(ph_1)$$
3. Fit known peaks in calibration and physics data → refine model



^{208}Tl delayed energy fit

Data-Driven Delayed Coincidence Energy Model



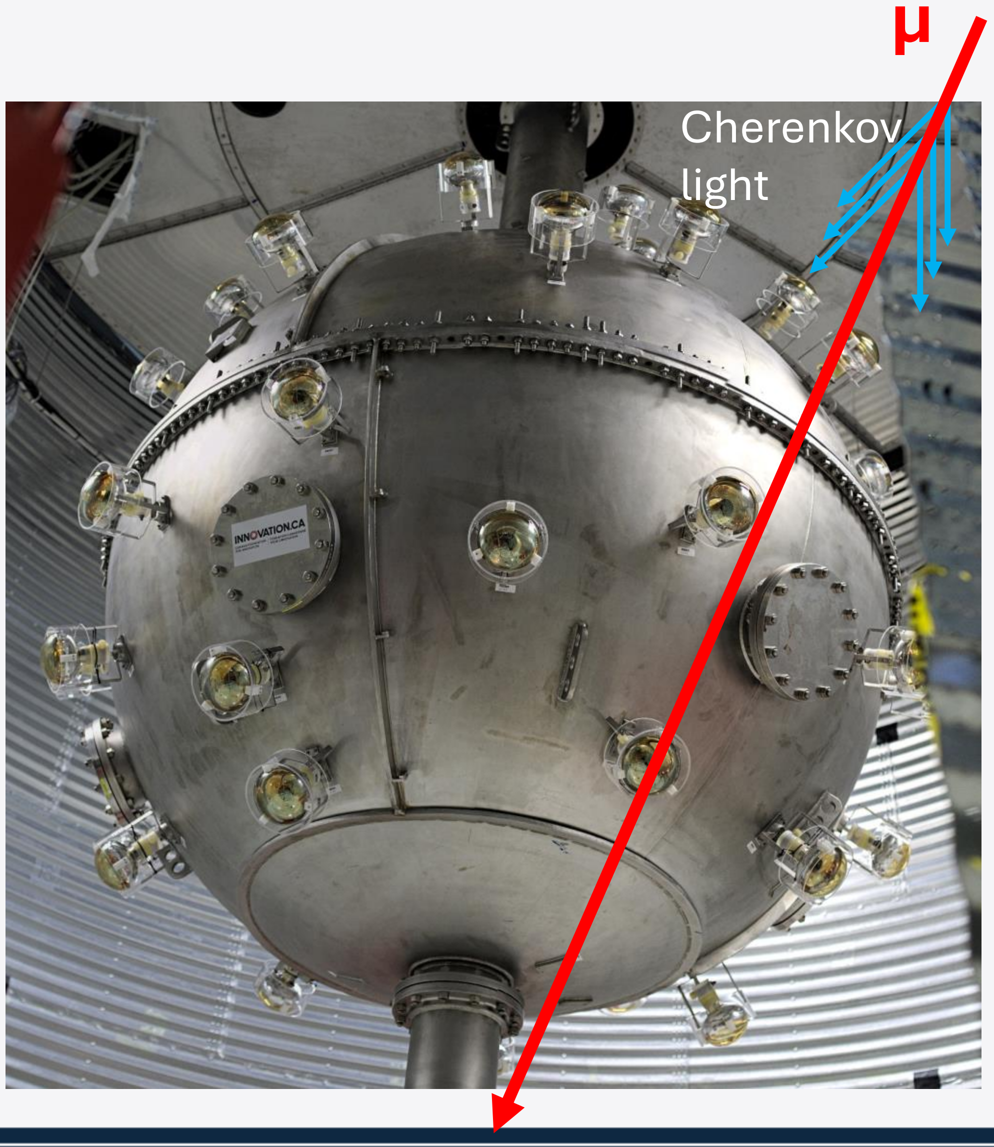
Example of fit results

Sample AmBe data waveform

Table of physics data delayed energy peak fits

Isotope	Expected Energy [MeV]	Fit Energy [MeV]	Fit Energy Sigma [MeV]
^{40}K	1.460	1.460	8.632e-2
^{214}Bi	1.764	1.730	8.637e-2
^{208}Tl	2.615	2.584	6.915e-2

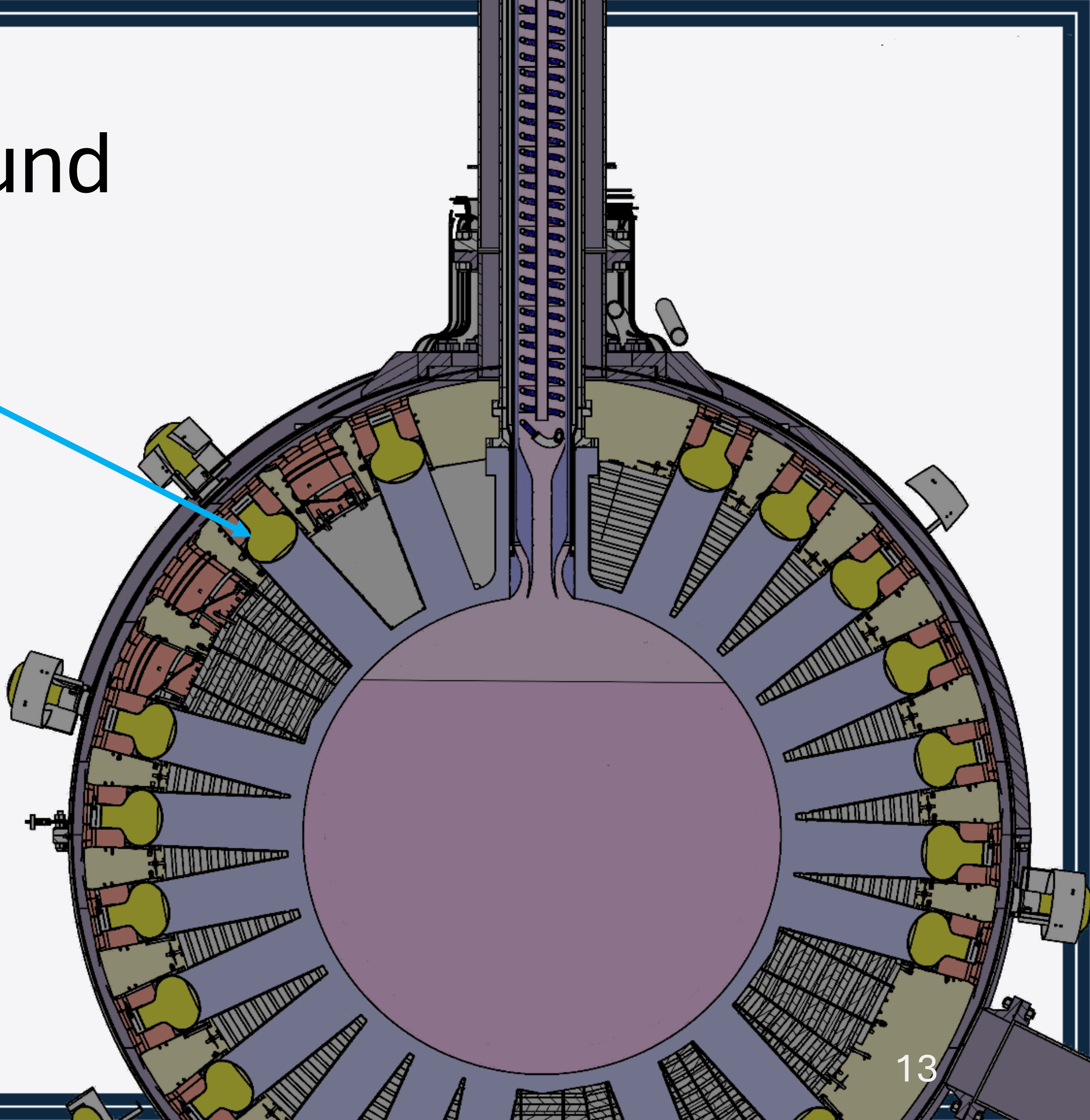
Cosmogenic Background



- Muons passing through or near the water tank
- Selecting scintillation events in LAr in prompt coincidence with a muon veto PMT trigger from Cherenkov light in the water tank.

Radiogenic Background

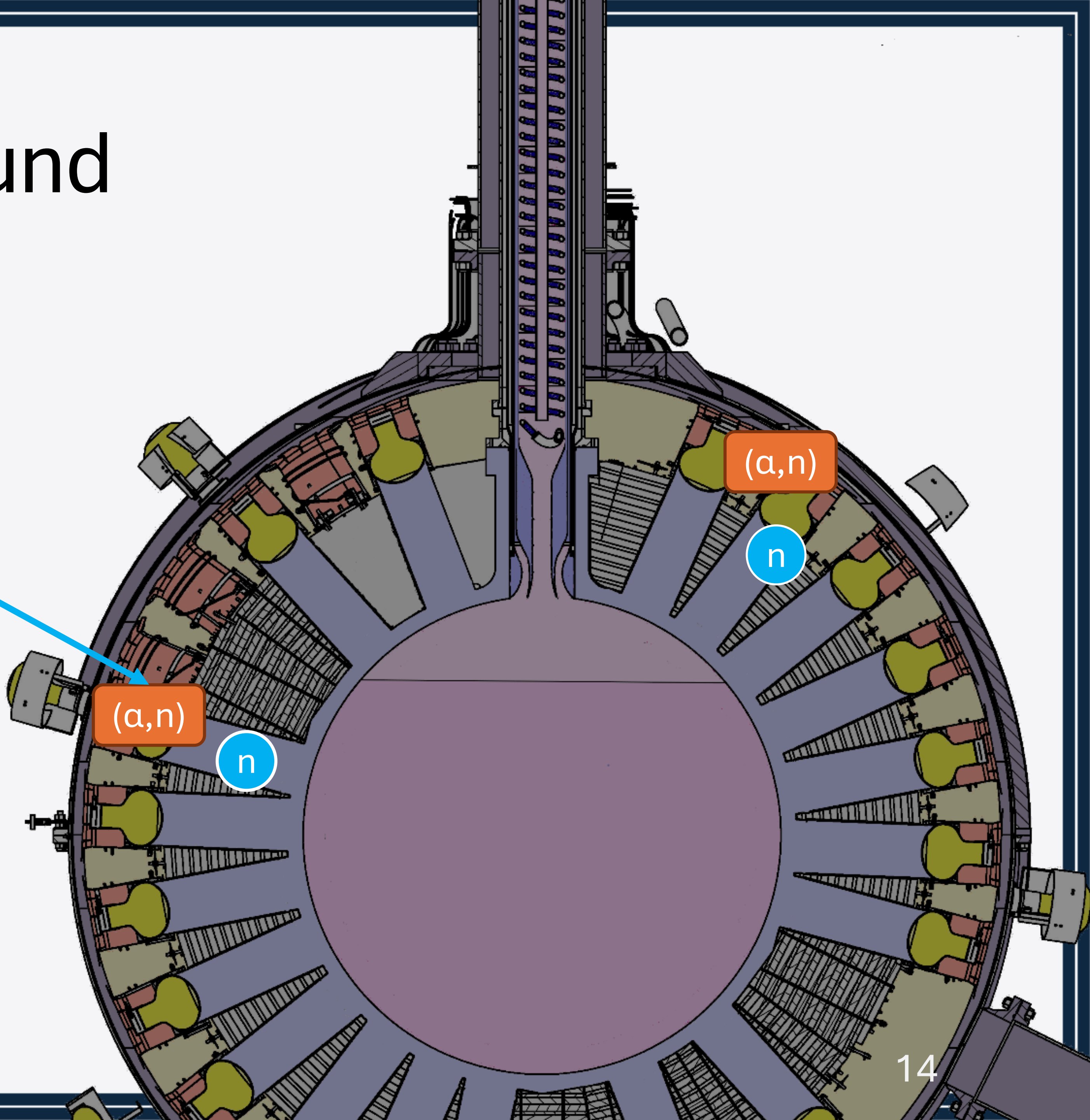
Main source : Neutron capture events from ^{238}U decay in the PMT glass



Radiogenic Background

Main source : Neutron capture events from ^{238}U decay in the PMT glass

Undergoes an (α, n) producing a neutron



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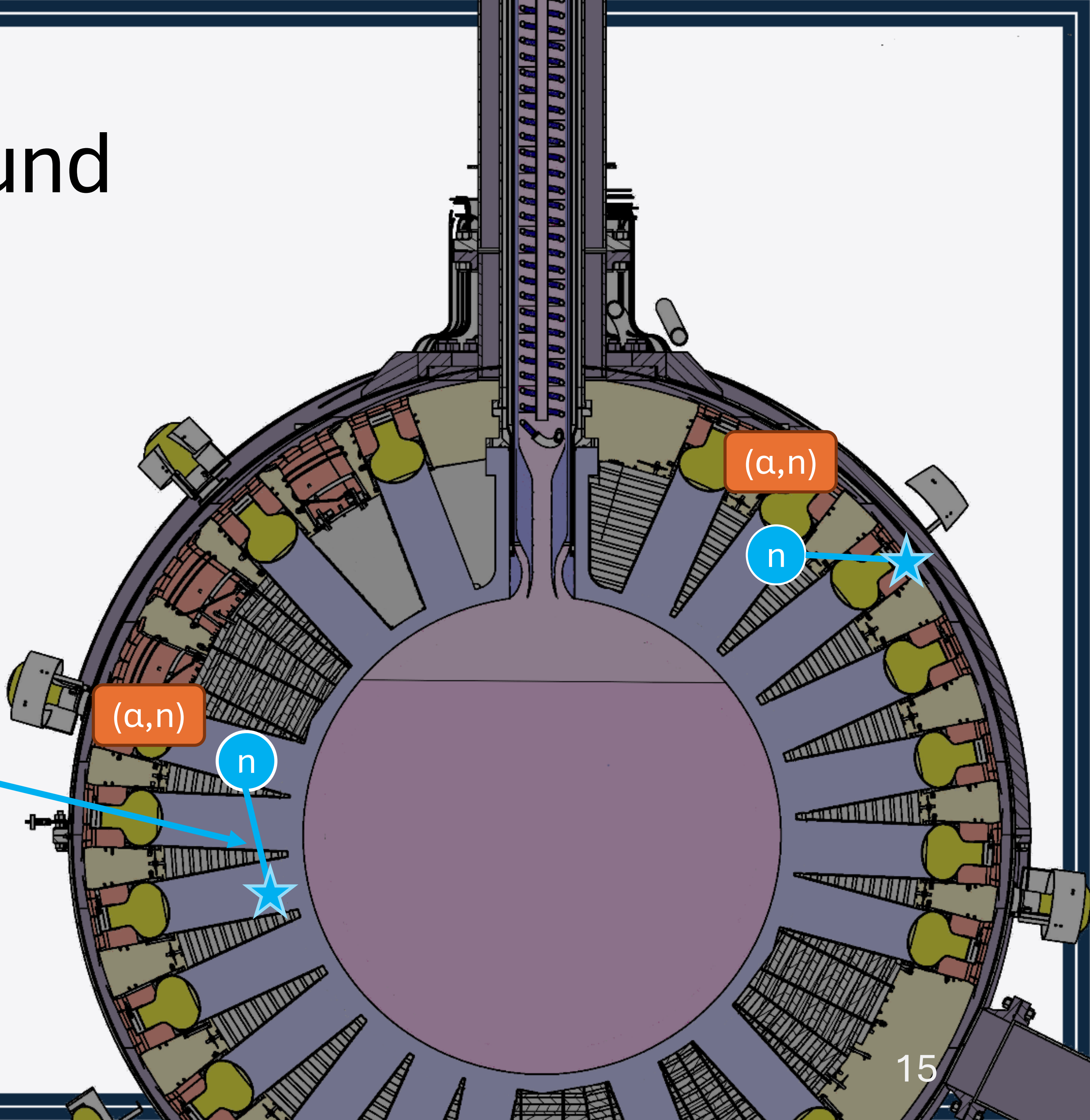
Neutron captured by material in the detector



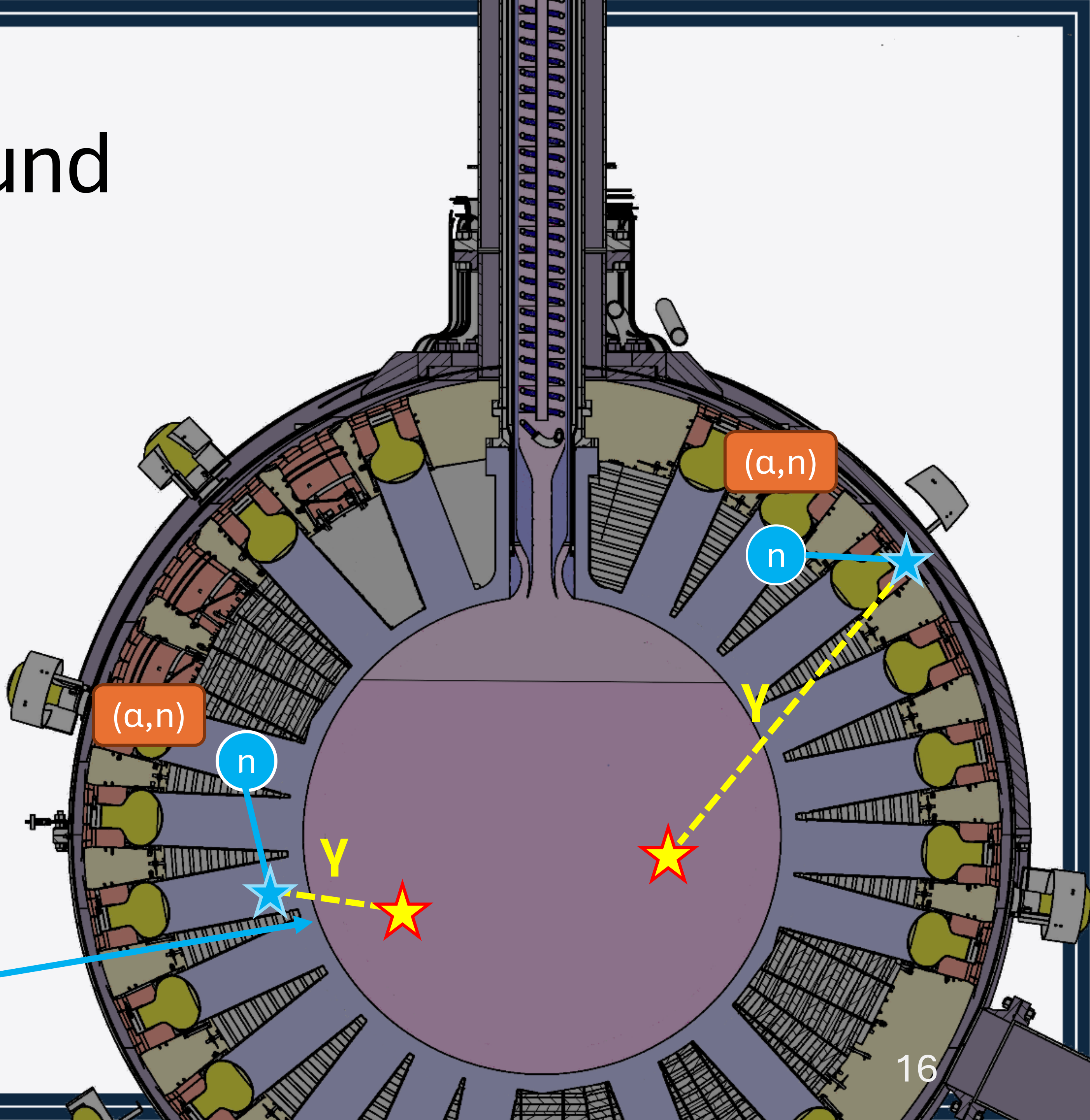
Radiogenic Background

Main source : Neutron capture events from ^{238}U decay in the PMT glass

Undergoes an (α, n) producing a neutron

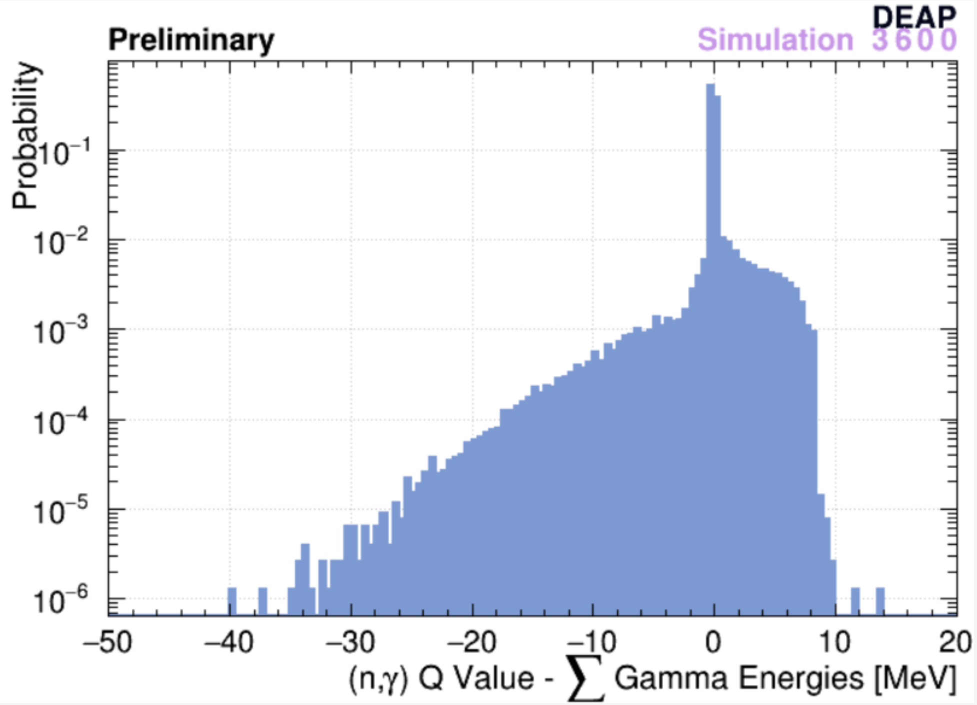
Neutron captured by material in the detector

Neutron capture isotope de-excites through a series of gamma rays



Neutron Capture Gammas

- Geant4 is not good at conserving energy in individual neutron capture interactions.



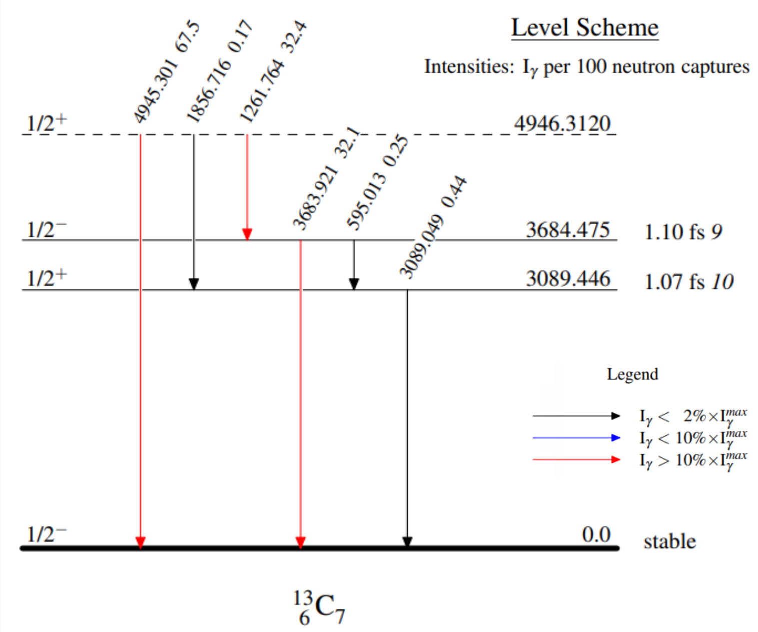
Example from MC truth:
^{56}Fe neutron capture to ^{57}Fe
Q Value = 7.65 MeV
Total gamma energy = 16.99 MeV
7 gammas emitted : 7.28, 4.81, 2.87, 0.90, 0.66, 0.35, 0.12 MeV

- The energy of each individual gamma are valid transition energies but not following a consistent de-excitation path

G4CASCADE – Modelling neutron capture gammas

- A Geant4 extension to conserve neutron capture energy and number of gammas given the neutron capture isotope and ENSDF database.

De-excitation from $^{12}C(n,\gamma)$



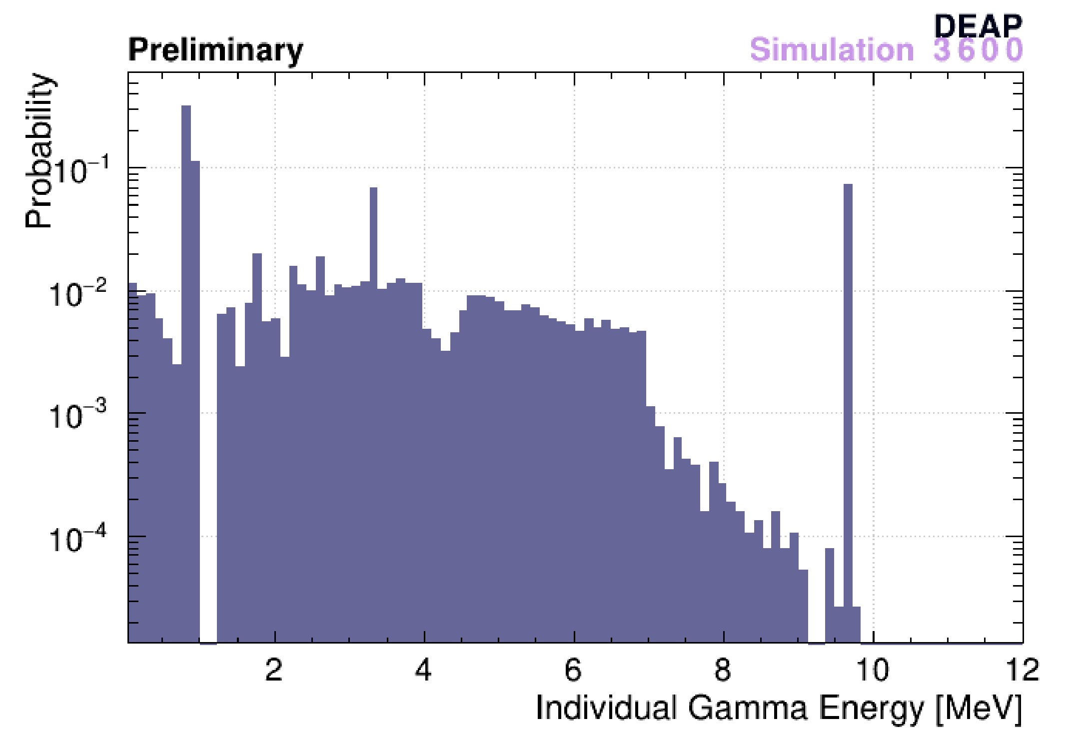
Source: 12C(N,G) E=TH file from https://www.nndc.bnl.gov/ensdf/

- Probability of de-excitation for a given branch is weighted according to its intensity.
- Process repeats at each new energy level in the cascade until the ground state.

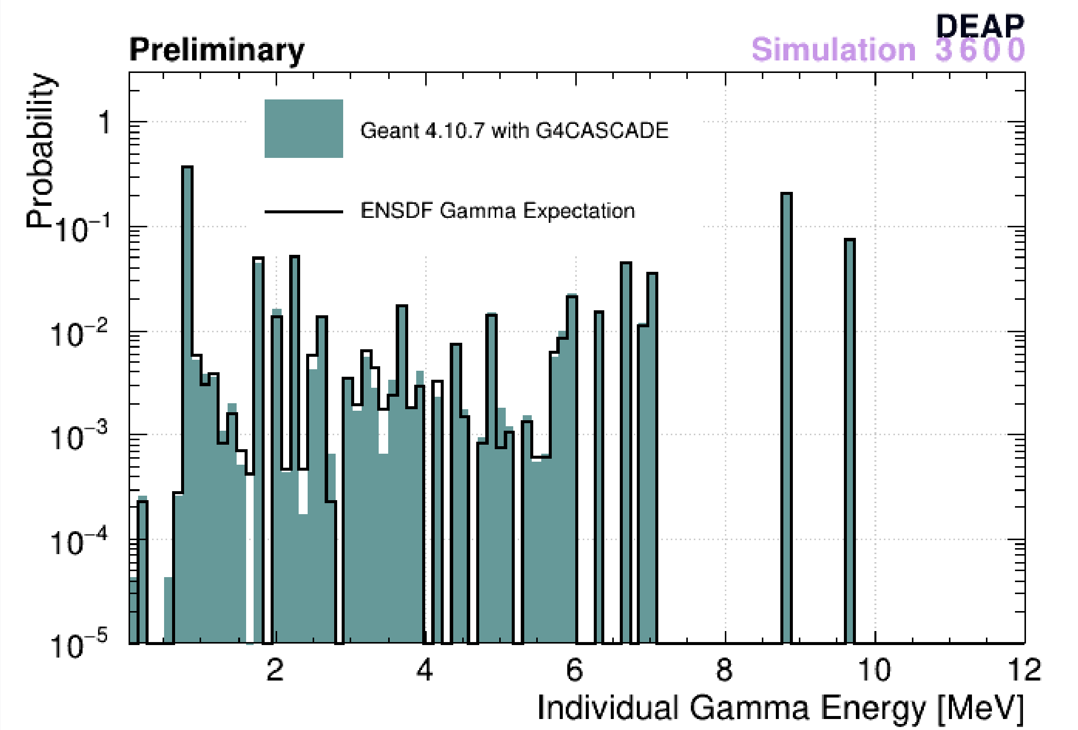
G4CASCADE – Modelling neutron capture gammas

Example of the energy of individual gammas emitted during ^{53}Cr neutron capture

Without G4CASCADE



With G4CASCADE



Summary

- DEAP-3600 is looking to make the first observation of neutrino absorption in ^{40}Ar using DEAP-3600. Future LAr experiments should be able to make higher statistic measurements.
- Current work focuses on finalizing radiogenic background model for the high energy region.