A New Tool for (α,n) Yield Calculations and Its Implications for DEAP-3600

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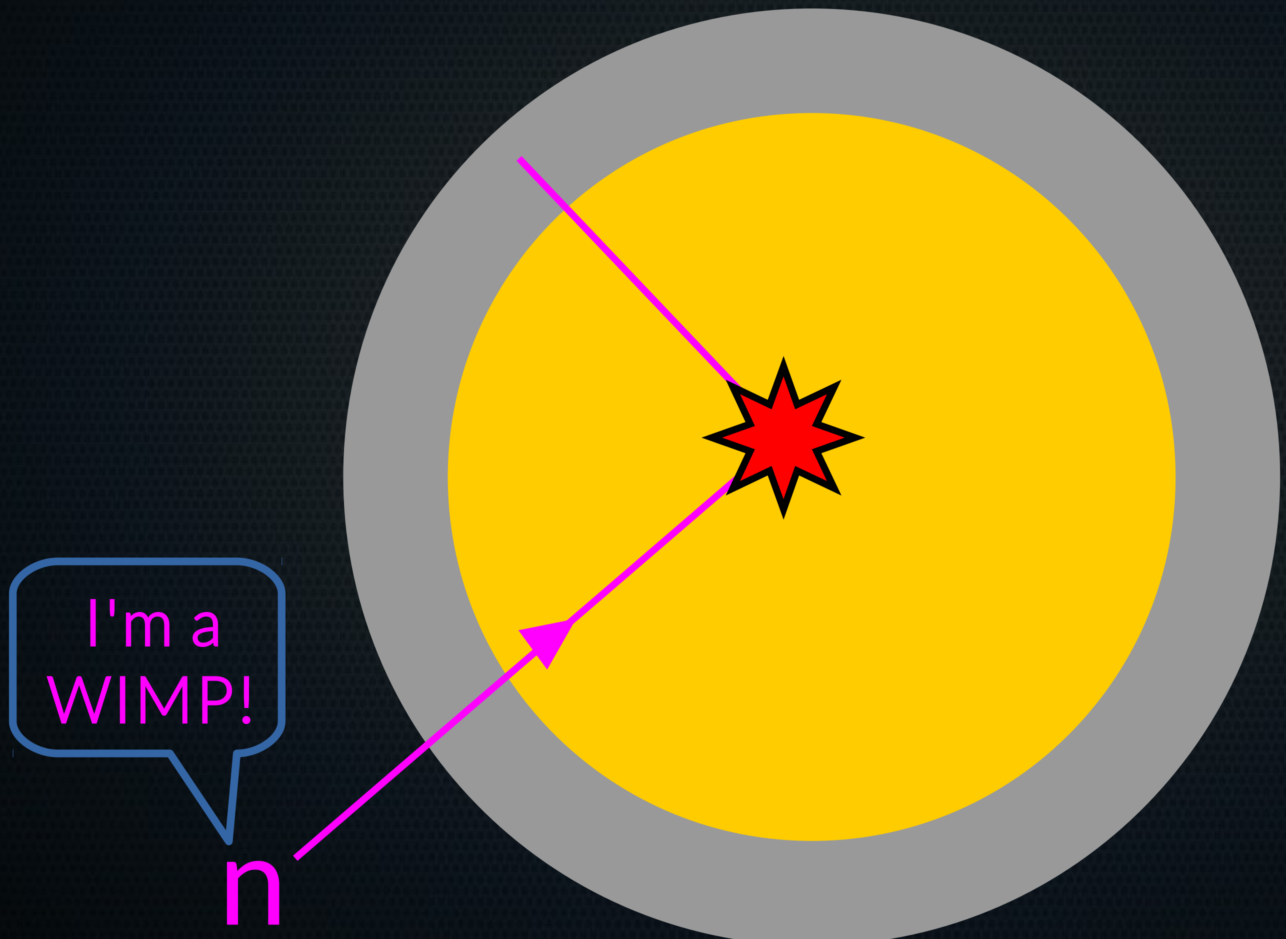
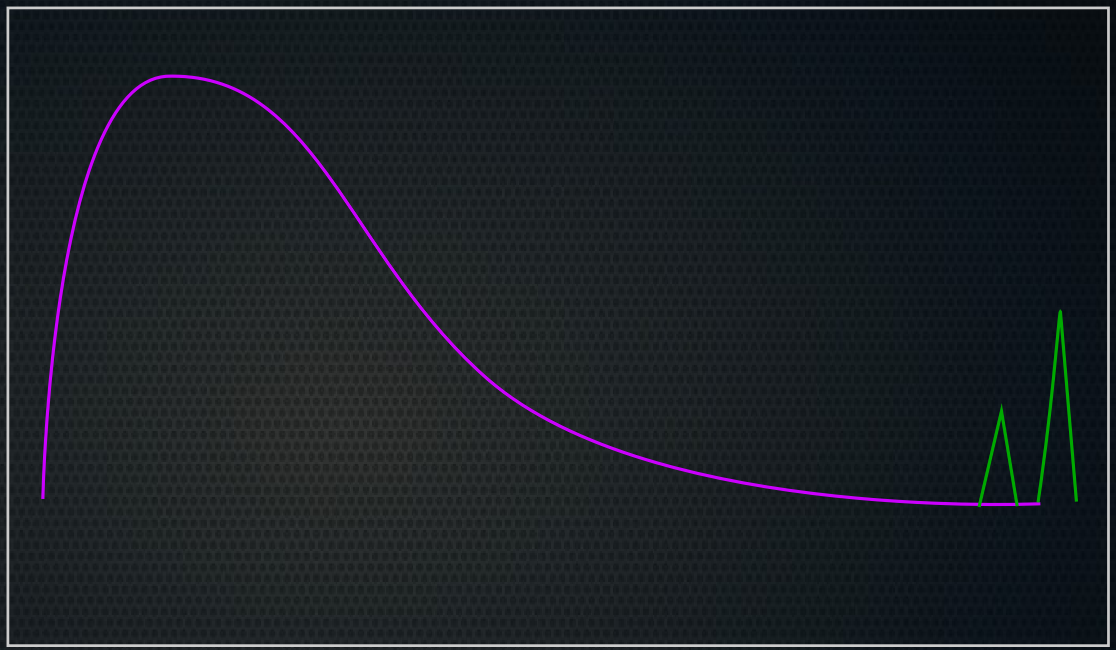
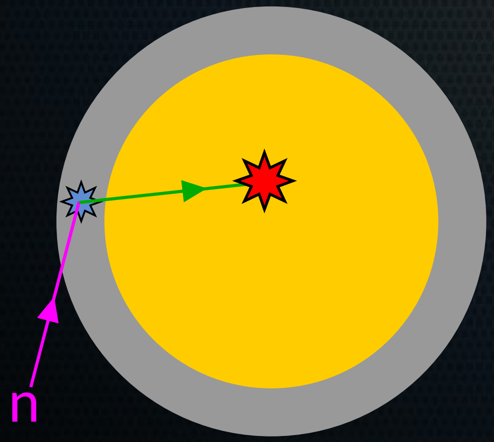
Carleton University
and the
DEAP-3600 Collaboration
(Low Radioactivity Techniques 2017)

The Importance of Neutron Backgrounds: WIMP Detectors



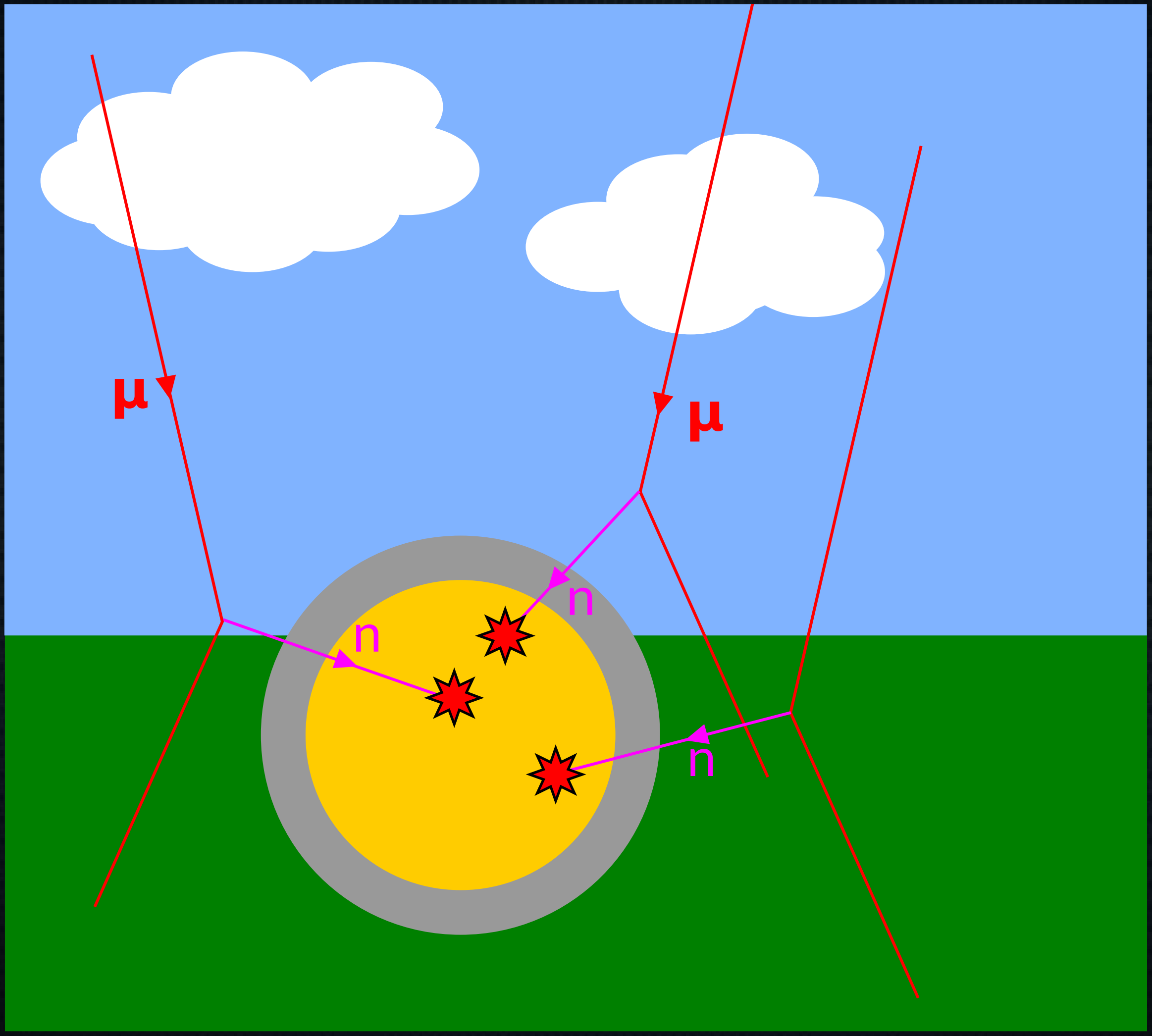
The Importance of Neutron Backgrounds: 0$\nu\beta\beta$ Detectors





High Sensitivity → Must Understand Neutron Backgrounds!

Sources of Neutrons: Cosmogenic



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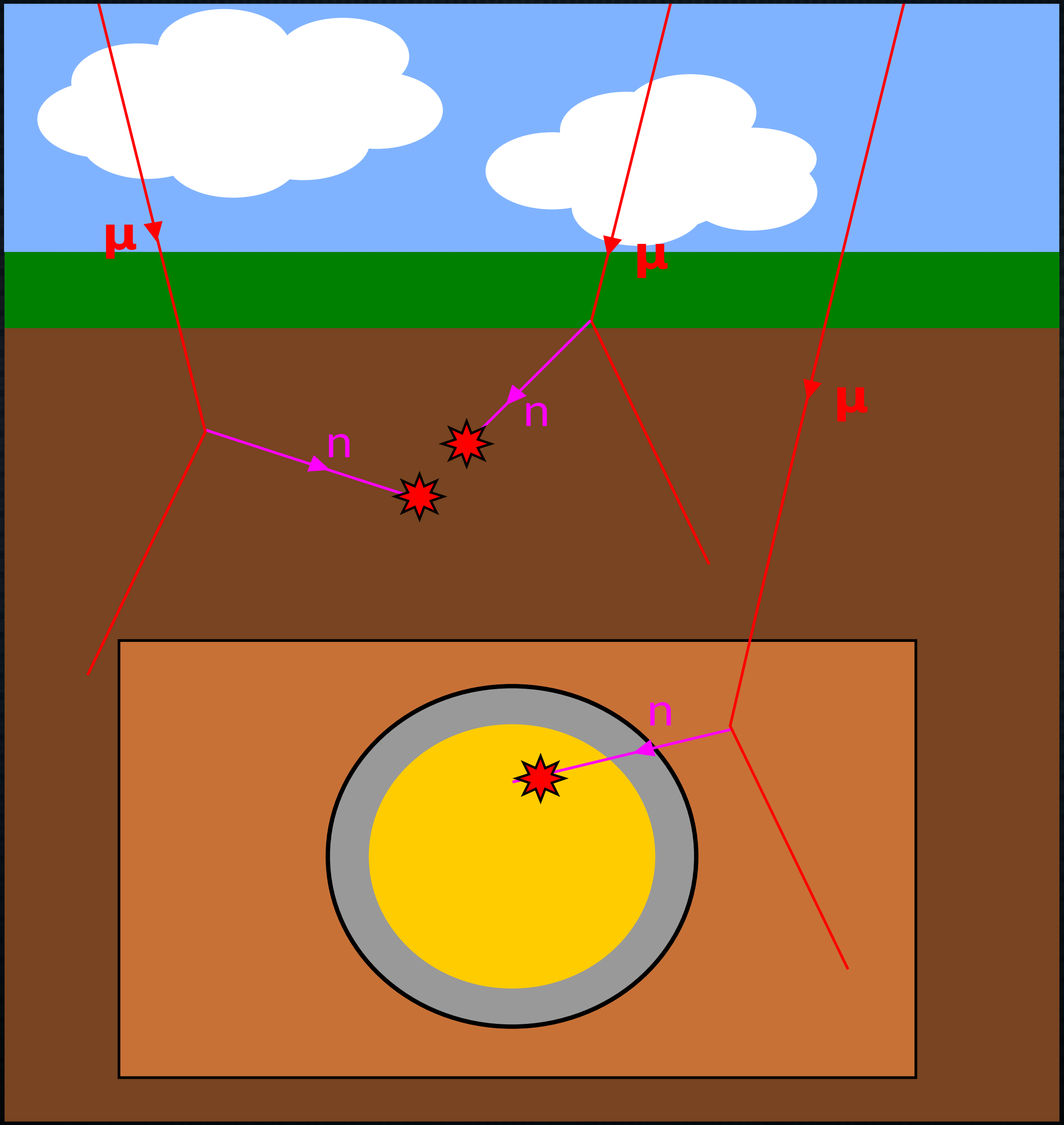

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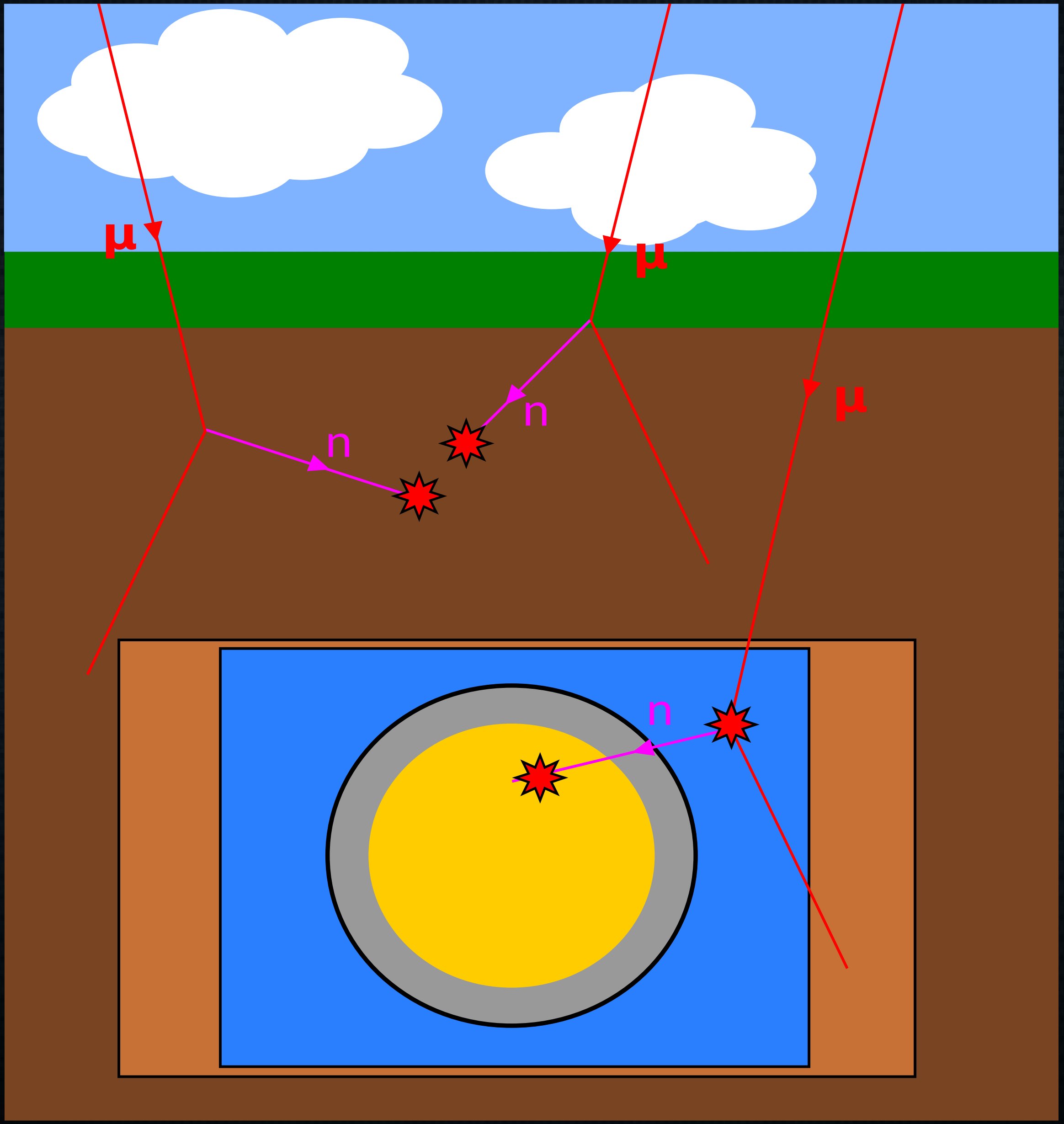
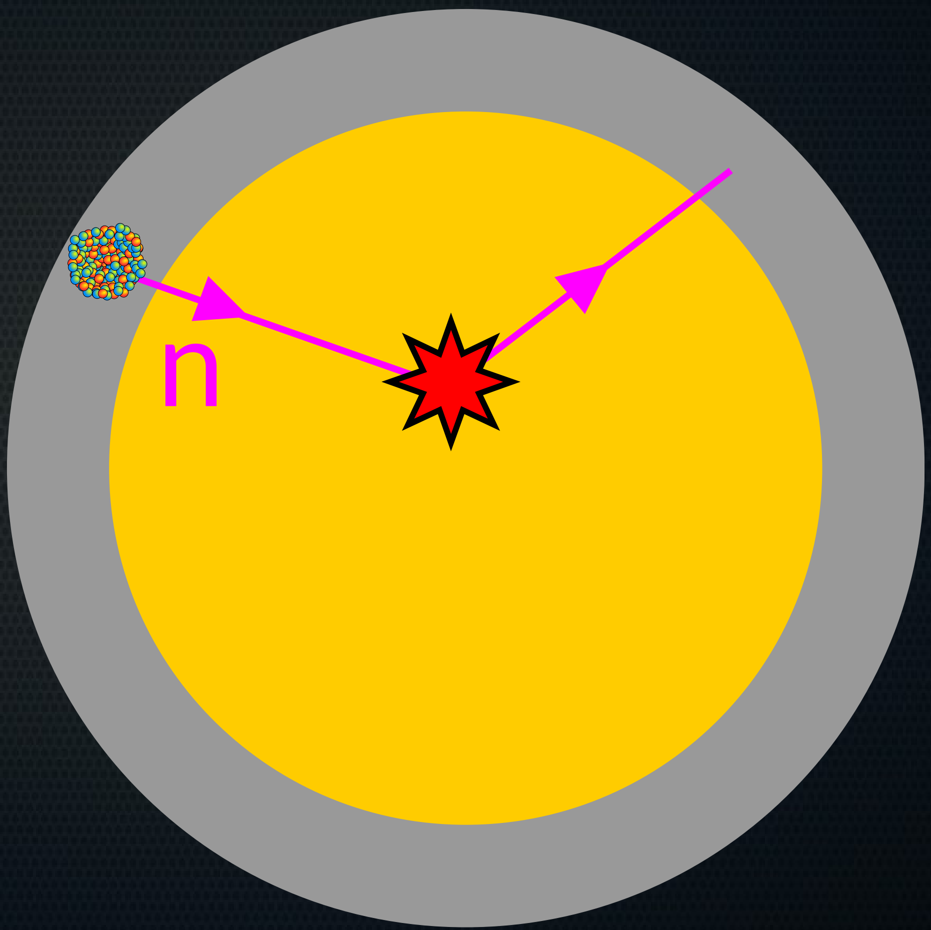


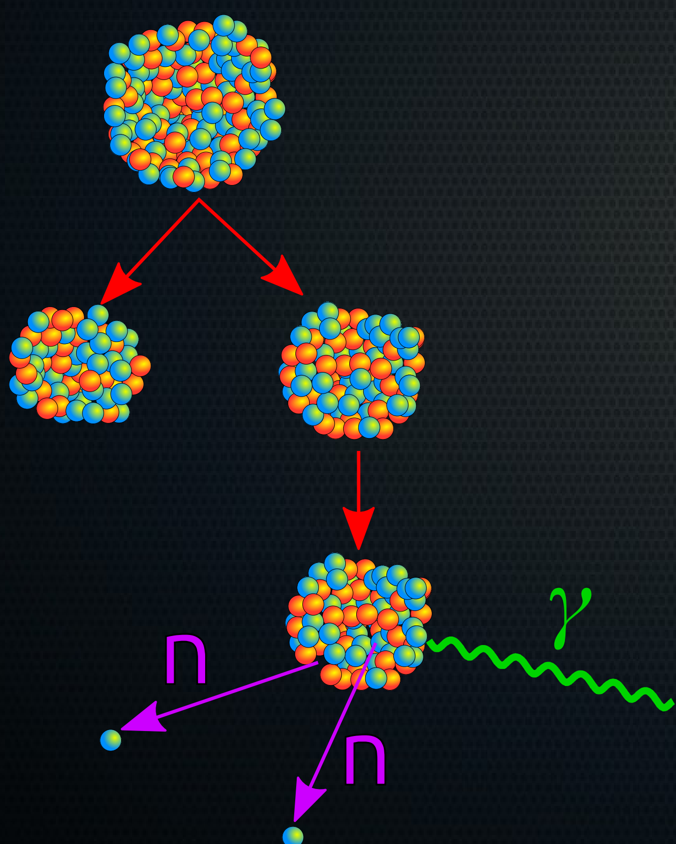
Sources of Neutrons: Radiogenic

- Due to nuclear reactions in detector components
- Depends on levels of ^{238}U, ^{235}U, and ^{232}Th contamination
- Produced by
  - Fission
  - Direct emission
  - (α,n) reaction

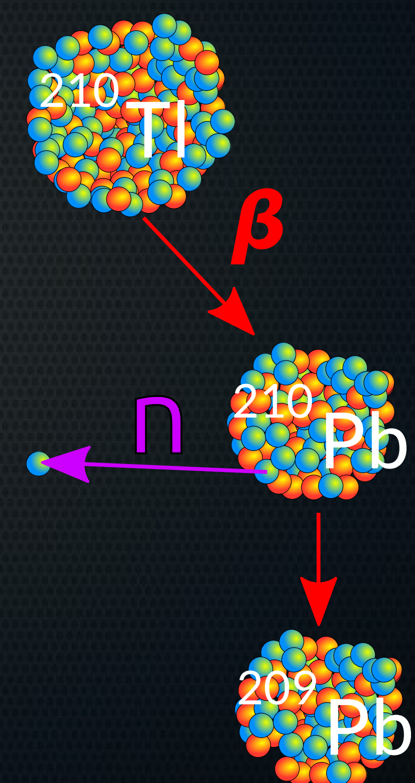


Sources of Neutrons: Radiogenic

^{238}U Fission:
1.1×10^{-6} n/s/Bq



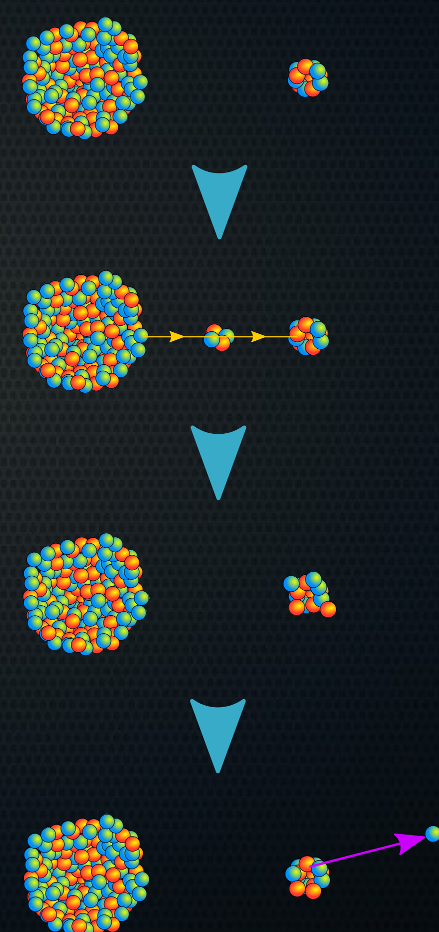
^{210}Tl Direct Neutron Emission:
1.5×10^{-8} n/s/Bq



Sources of Neutrons: Radiogenic: The (α,n) Reaction

- Rate depends on concentration of all α-emitting contaminants in decay chains
- Depends on composition of material
- Need to calculate (α,n) yield of each material

(**α**,n) Reaction



Neutron Calculator Based On TALYS

See paper at arXiv:1702.02465 (Submitted to NIM A)
Download: github.com/shawest/neucbot

NeuCBOT

- Calculates (α,n) yields and neutron energy spectra for given decay chains or lists of α energies in arbitrary materials
- Complete stopping power database generated by SRIM code (Ziegler et al.)
- Complete database of (α,n) cross sections and neutron spectra for all naturally occurring isotopes for α energies below 10 MeV
  - Integrates with TALYS to further extend database

NeuCBOT User Input

- Material Composition
  - List of chemical symbols, isotopes (0 for natural abundance), and percent mass

```
# Example Semi-Heavy Water
H 1 5.3
H 2 10.5
O 0 84.2
```

- α Energy List
  - Energy in MeV followed by percent probability

```
# Example Alpha Source
5 100
6 50
```

NeuCBOT User Input

- Material Composition
  - List of chemical symbols, isotopes (0 for natural abundance), and percent mass

```
# Example Semi-Heavy Water
H 1 5.3
H 2 10.5
O 0 84.2
```

- Isotope List
  - Isotope symbol followed by percent branching ratio
  - Looks up α decay data from ENSDF database

```
# Th232 Decay Chain Alpha-emitters
Th232 100
Th228 100
Ra224 100
Rn220 100
Po216 100
Bi212 35.94
Po212 64.06
```

NeuCBOT Calculations

$$Y(T_n) = \sum_\alpha P_\alpha \sum_m \frac{N_A C_m}{A_m} \sum_{T'_\alpha \in \{T_\alpha, T_\alpha - \Delta T'_\alpha, \ldots, 0\}} \frac{\sigma_m(T'_\alpha, T_n)}{S(T'_\alpha)} \Delta T'_\alpha$$

- T_n: Outgoing neutron energy
- P_α: α probability (from user input+ENSDF)
- C_m: Target nucleus mass fraction in material (user input)
- A_m: Target nucleus mass number
- $T'_\alpha \in \{T_\alpha, T_\alpha - \Delta T'_\alpha, \ldots, 0\}$: α energy (from user input+ENSDF)
- $\sigma_m(T'_\alpha, T_n)$: Cross section (from TALYS)
- $S(T'_\alpha)$: Mass stopping power (from SRIM)

NeuCBOT Calculations

$$Y(T_n) = \sum_{\alpha} P_{\alpha} \sum_{m} \frac{N_A C_m}{A_m} \sum_{T'_{\alpha} \in \{T_{\alpha}, T_{\alpha} - \Delta T'_{\alpha}, \ldots, 0\}} \frac{\sigma_m(T'_{\alpha}, T_n)}{S(T'_{\alpha})} \Delta T'_{\alpha}$$

α probability (from user input+ENSDF)

Target nucleus mass fraction in material (user input)

Cross section (from TALYS)

Outgoing neutron energy

Target nucleus mass number

Mass stopping power (from SRIM)

α energy (from user input+ENSDF)

NeuCBOT Calculations

$$Y(T_n) = \sum_\alpha P_\alpha \sum_m \frac{N_A C_m}{A_m} \sum_{T'_\alpha \in \{T_\alpha, T_\alpha - \Delta T'_\alpha, \ldots, 0\}} \frac{\sigma_m(T'_\alpha, T_n)}{S(T'_\alpha)} \Delta T'_\alpha$$

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NeuCBOT Calculations

α probability (from user input+ENSDF)

Target nucleus mass fraction in material (user input)

Cross section (from TALYS)

$$Y(T_n) = \sum_{\alpha} P_{\alpha} \sum_{m} \frac{N_A C_m}{A_m} \sum_{T'_\alpha \in \{T_\alpha, T_\alpha - \Delta T'_\alpha, \ldots, 0\}} \frac{\sigma_m(T'_\alpha, T_n)}{S(T'_\alpha)} \Delta T'_\alpha$$

Outgoing neutron energy

Target nucleus mass number

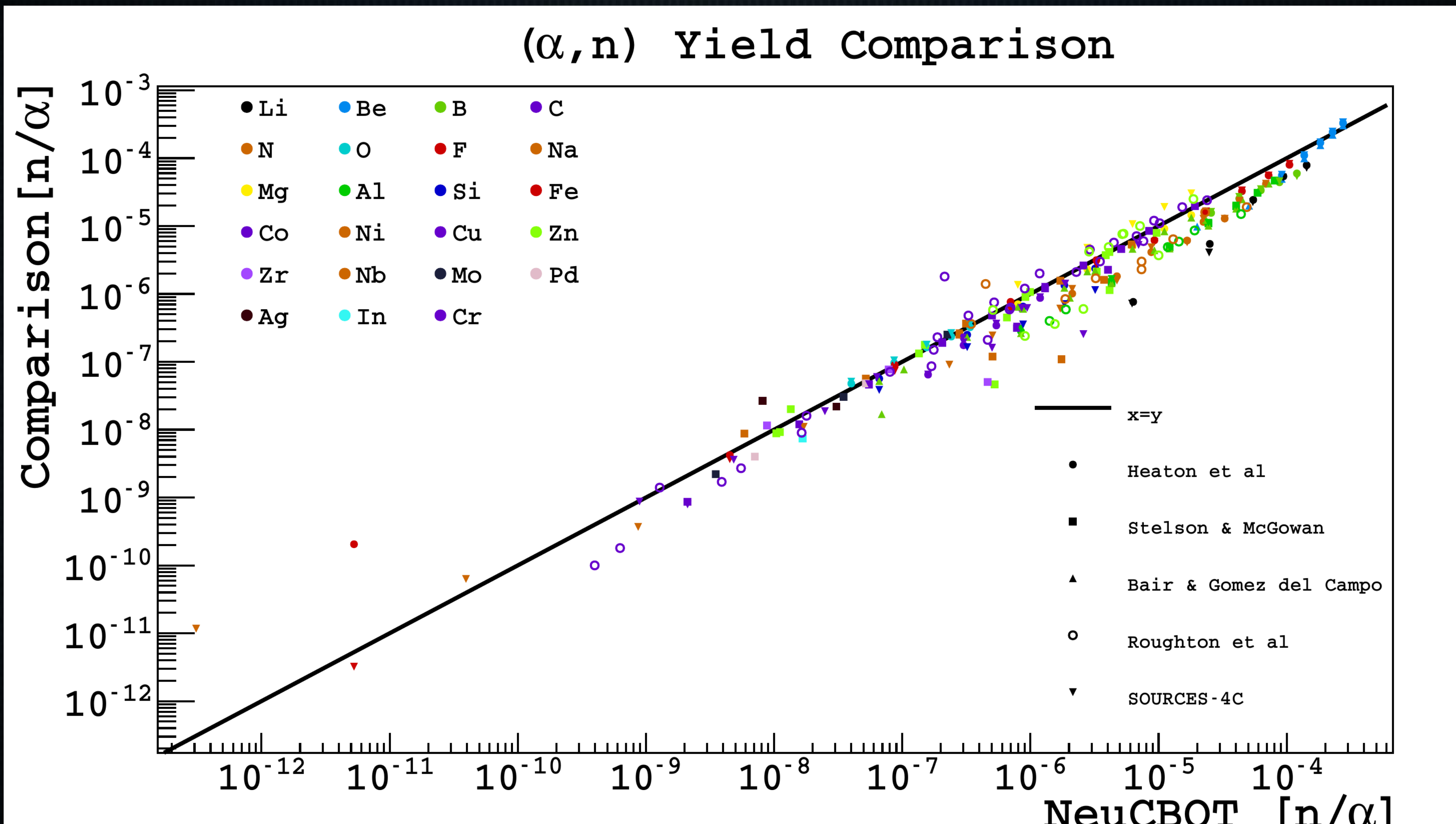
Mass stopping power (from SRIM)

α energy (from user input+ENSDF)

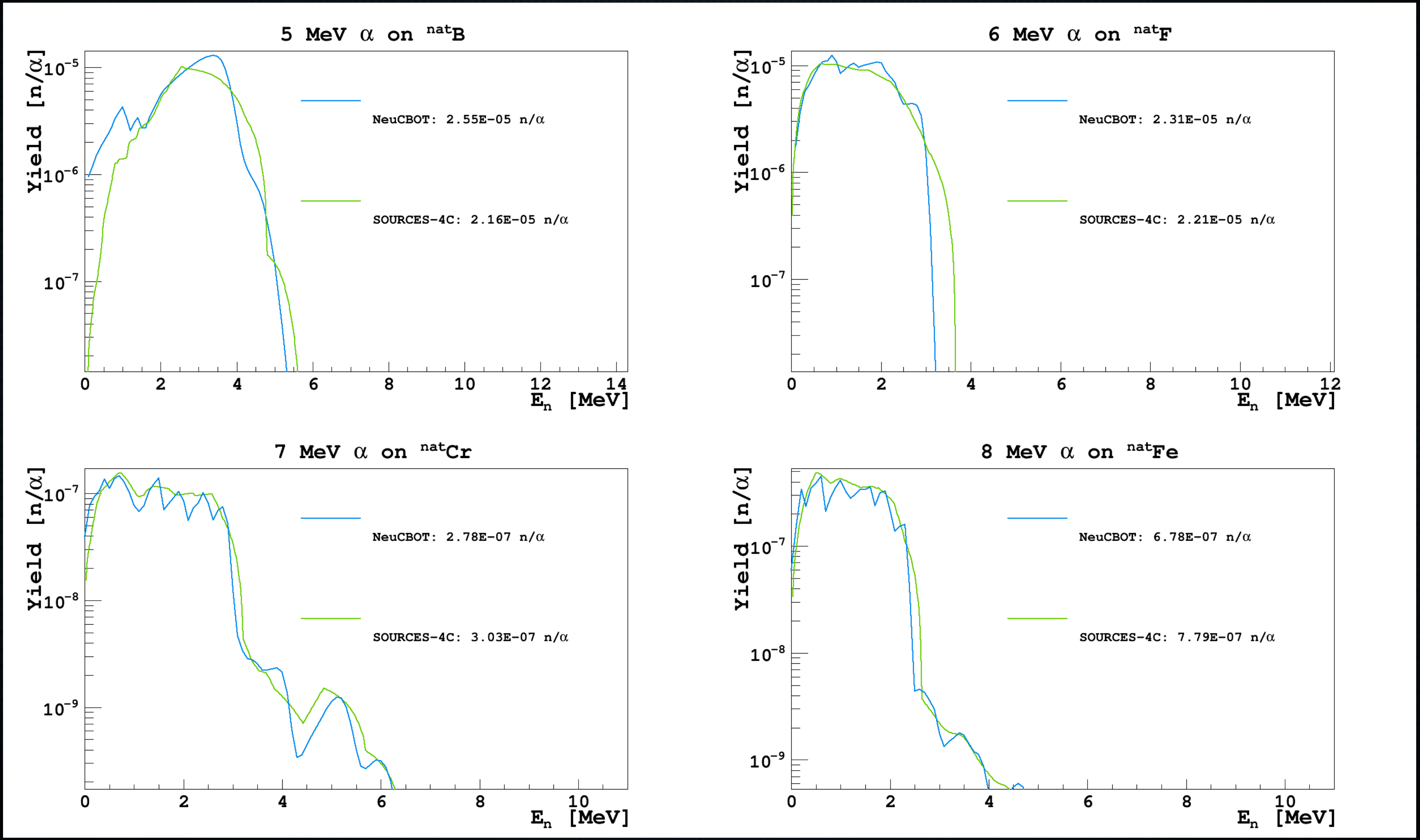
Validation

- TALYS and the TENDL database have been extensively validated, themselves
- Compare to measured (α,n) yields
- Compare to SOURCES-4C?
  - Extended cross section data from JENDL library and EMPIRE code

Validation: General agreement, but NeuCBOT Slightly Systematically Higher



Validation: NeuCBOT and SOURCES spectra agree well

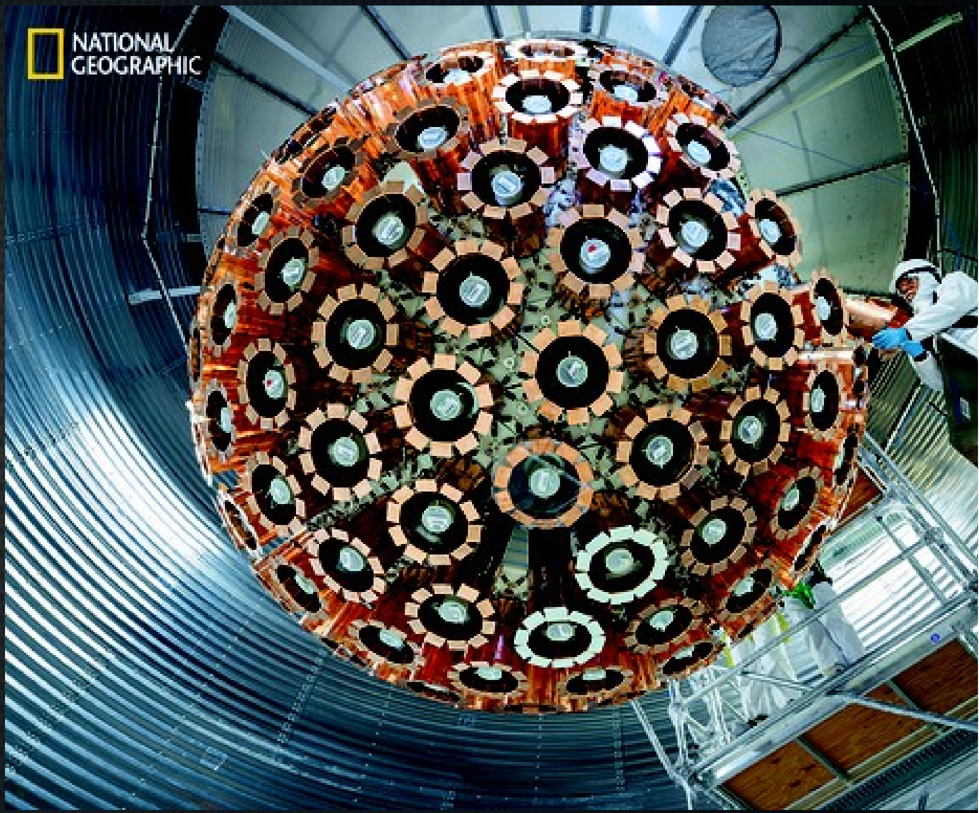


Future Developments

- Web interface
- Calculate gamma spectrum in coincidence with neutrons
- Options to interface with nuclear databases instead of TALYS
  - e.g. ENDF, JENDL, etc.

DEAP-3600

- Located at SNOLAB
- Over 3 tonnes LAr
- Viewed by 255 PMTs
- 50 cm of acrylic buffer between PMTs and LAr
- Inside water tank muon veto



DEAP-3600 Neutron Background

- Radioactive contamination measured via *ex-situ* γ-counting
- Use NeuCBOT to estimate yield of each primary component
- Simulate neutrons in GEANT4 to estimate how many may look like a WIMP

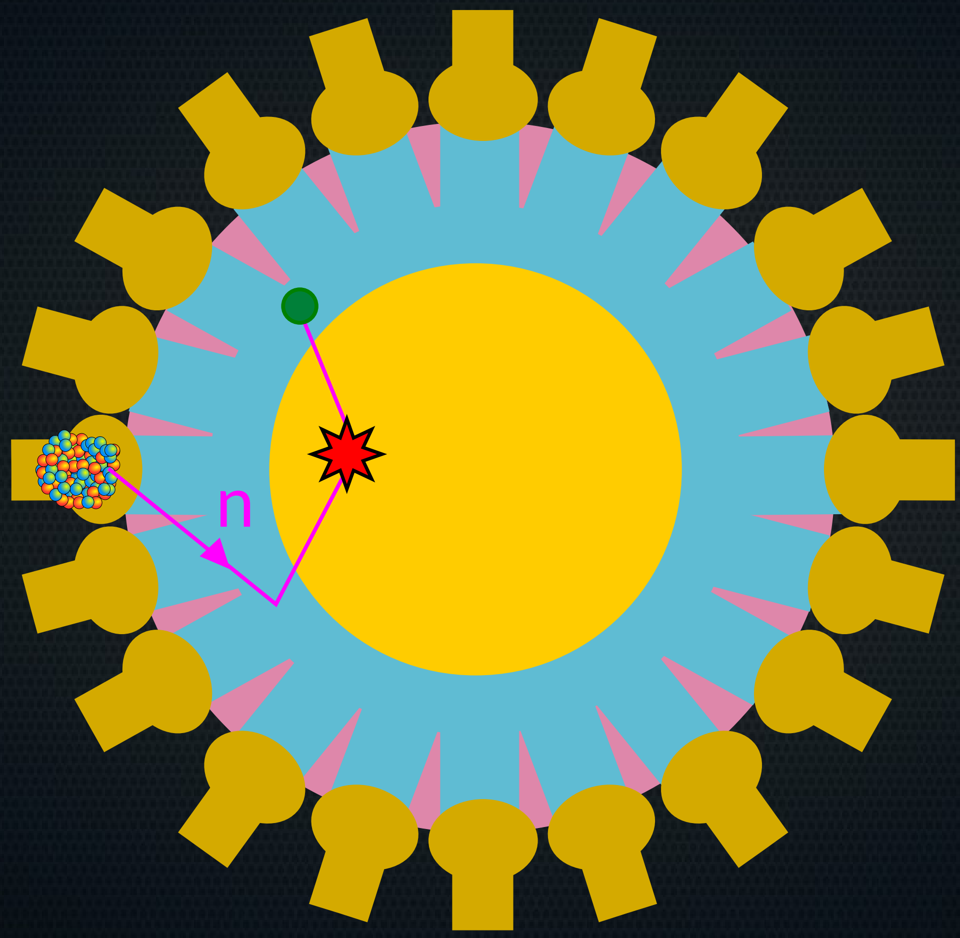
DEAP-3600 Neutron Yields

NeuCBOT	n/s/Bq			
Material	**U238 upper**	**U238 lower**	**U235**	**Th232**
Borosilicate Glass	3.93E-06	1.76E-05	2.56E-05	2.43E-05
Acrylic	2.19E-07	9.72E-07	1.42E-06	1.33E-06
Invar	2.06E-12	2.58E-07	1.84E-07	1.08E-06
TPB	3.15E-07	1.35E-06	1.96E-06	1.84E-06
Polyethylene	2.52E-07	1.09E-06	1.58E-06	1.49E-06
Polystyrene	3.01E-07	1.29E-06	1.88E-06	1.77E-06
Stainless Steel	1.31E-09	5.52E-07	4.42E-07	1.96E-06
Argon	8.82E-08	1.41E-05	1.72E-05	2.64E-05

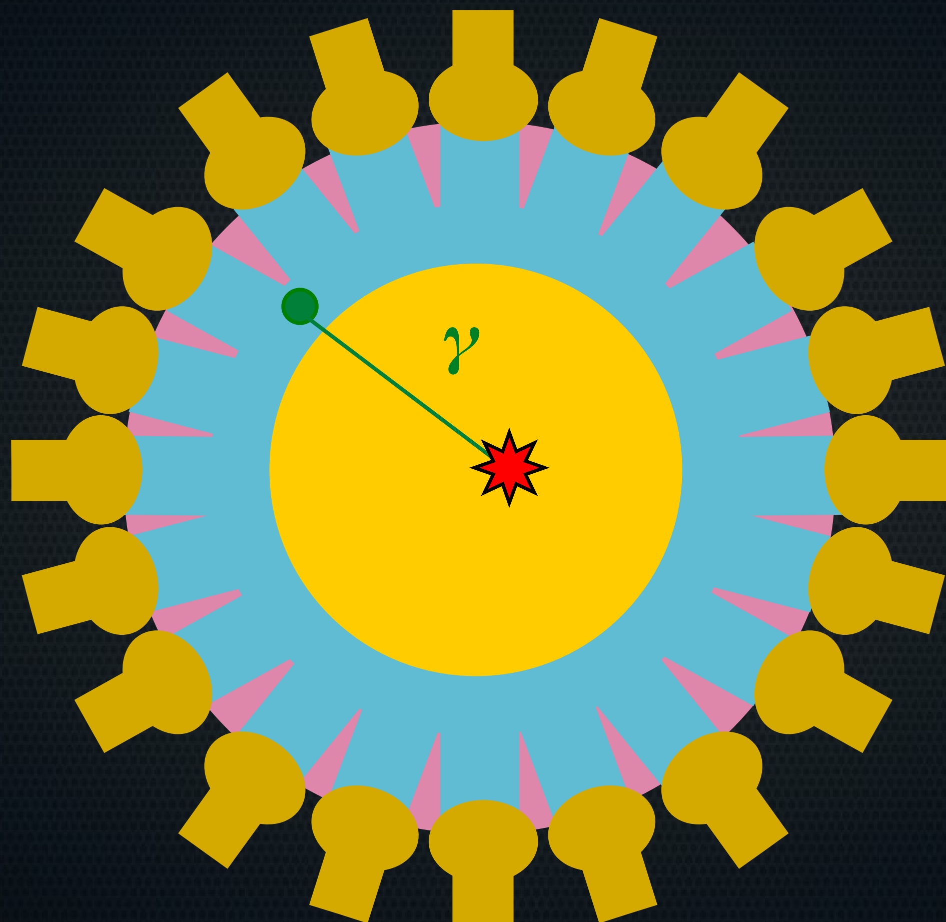
DEAP-3600 Neutron Rates

- Expect 143,000±4,000 neutrons/year
  - Predominantly in PMT glass
- The vast majority of these neutrons will fail to make it into the LAr
  - Geometric factors
  - Blocked by acrylic buffer
- Monte Carlo indicate that ~18.6 n/year will produce a signal in the LAr above 11 keVee
  - Most will be outside ROI and fiducial cuts

Life of a DEAP Neutron

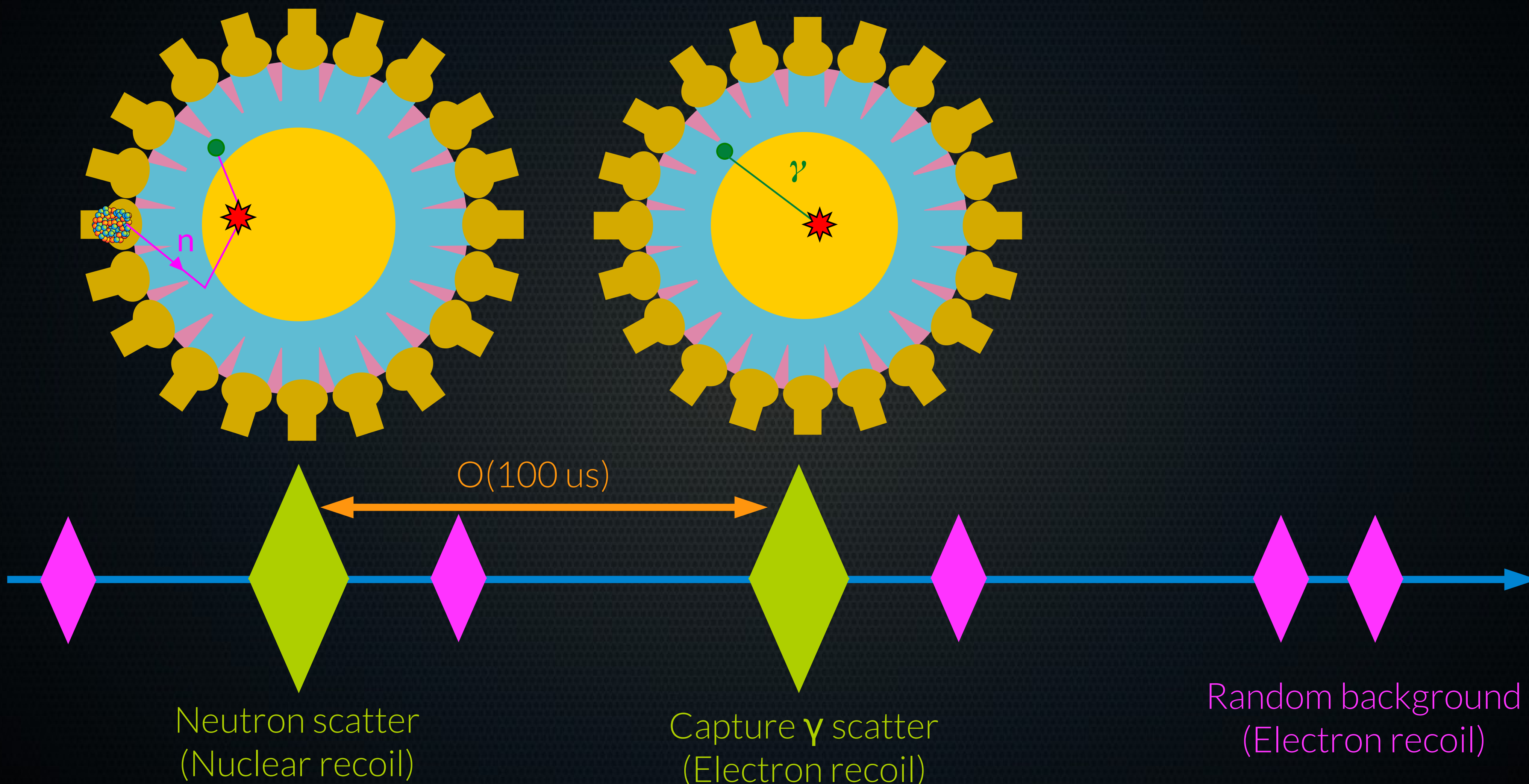


Life of a DEAP Neutron



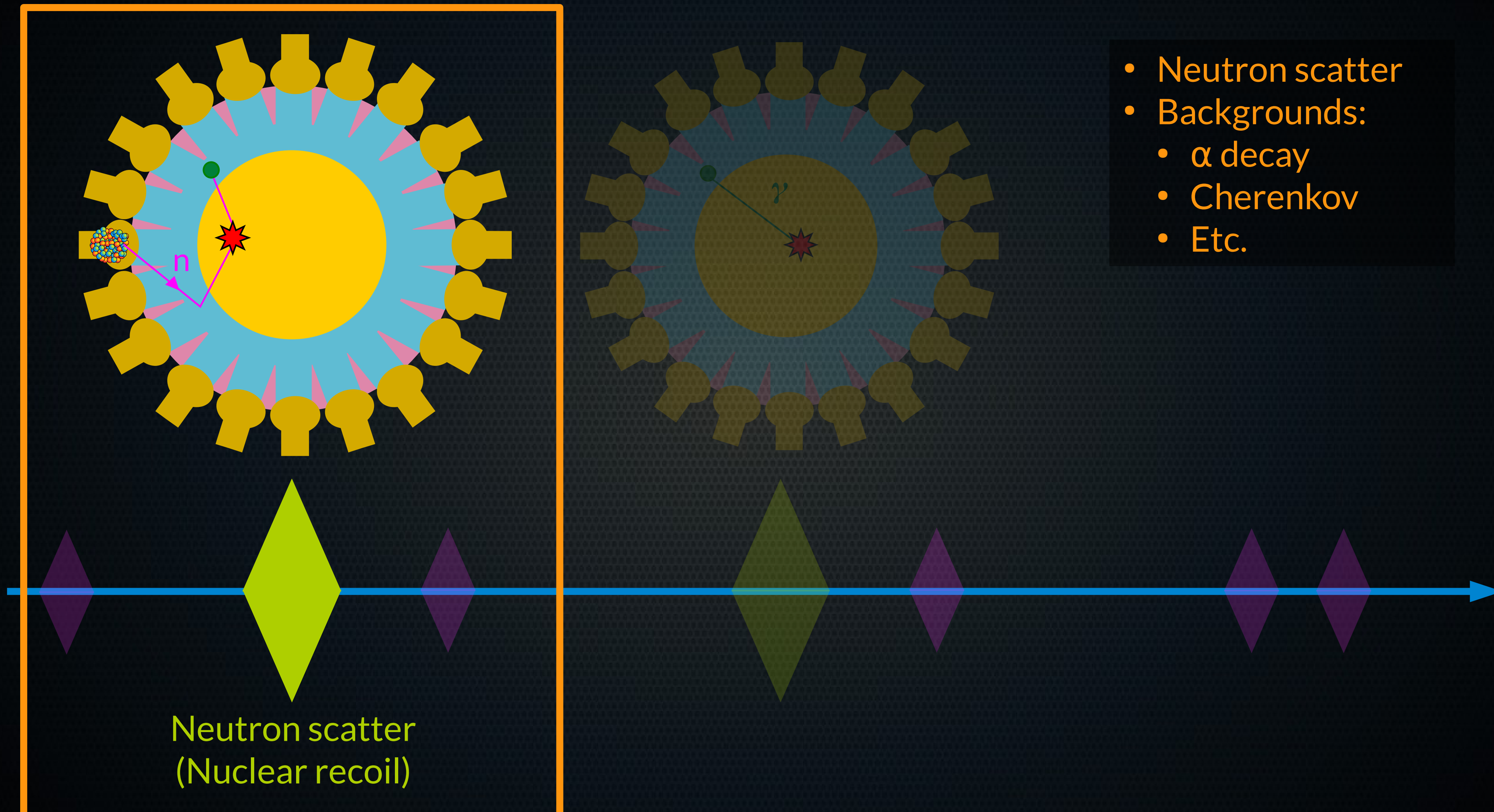
Can we use these coincidences to tag neutrons and constrain the neutron rate?

In Situ Neutron Search: Strategy



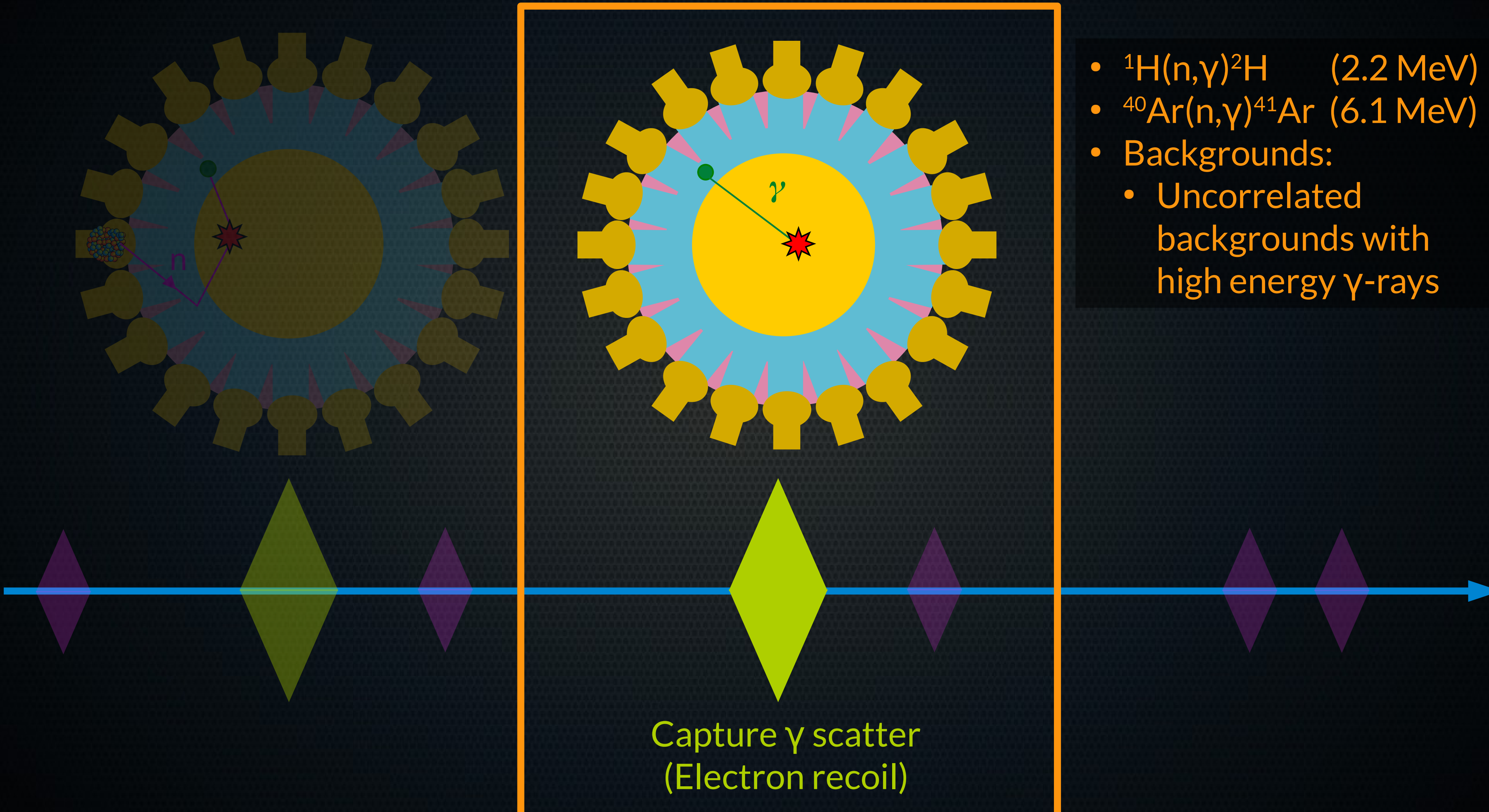
1) Identify Neutron Scatter Candidates

- Neutron scatter
- Backgrounds:
  - α decay
  - Cherenkov
  - Etc.



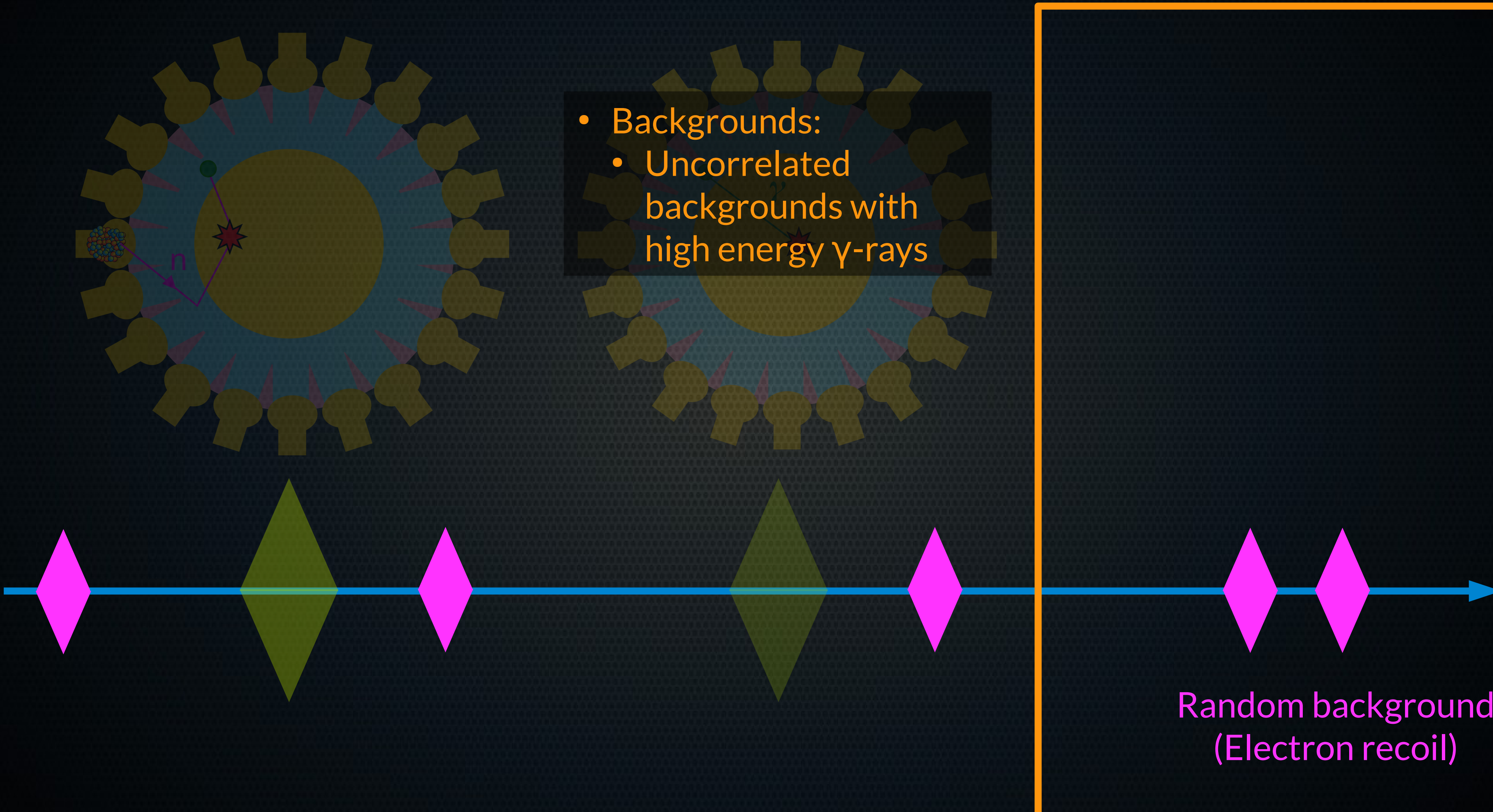
2) Identify Neutron Capture Candidates

- $^{1}H(n,\gamma)^{2}H$ (2.2 MeV)
- $^{40}Ar(n,\gamma)^{41}Ar$ (6.1 MeV)
- Backgrounds:
  - Uncorrelated backgrounds with high energy γ-rays

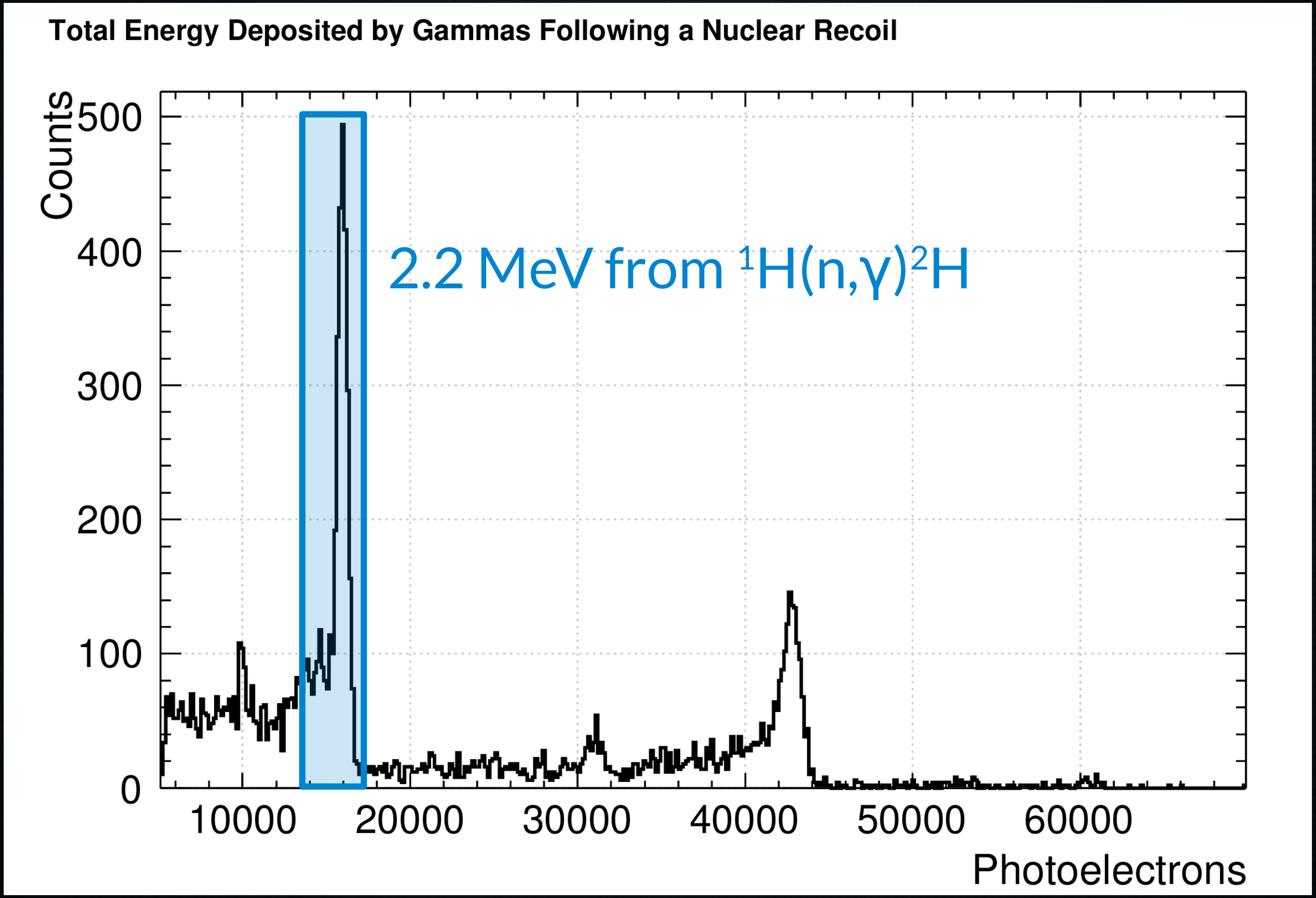


3) Measure Uncorrelated ER Rate

- Backgrounds:
  - Uncorrelated backgrounds with high energy γ-rays



AmBe Calibration: Clear Neutron Capture Signals



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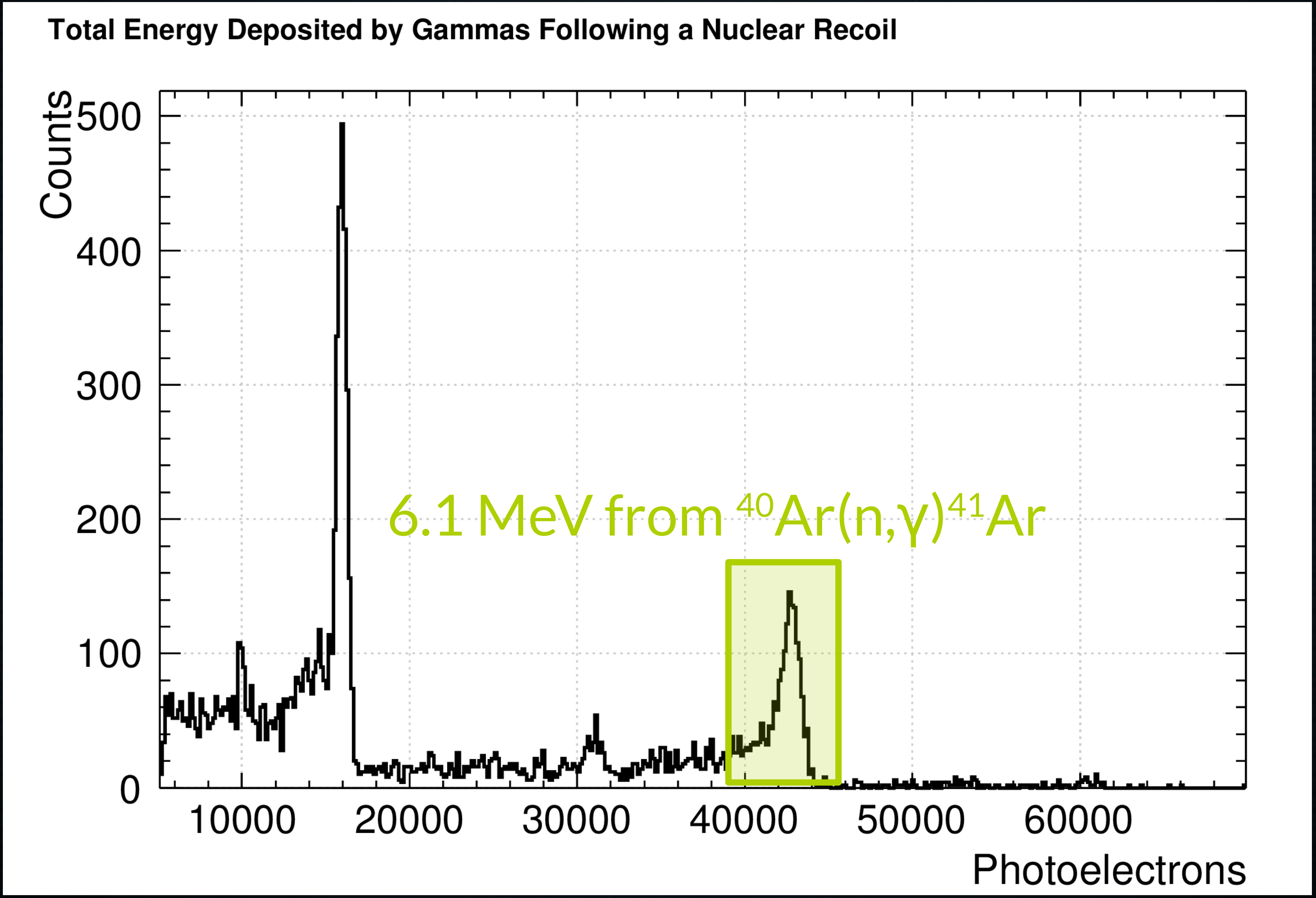
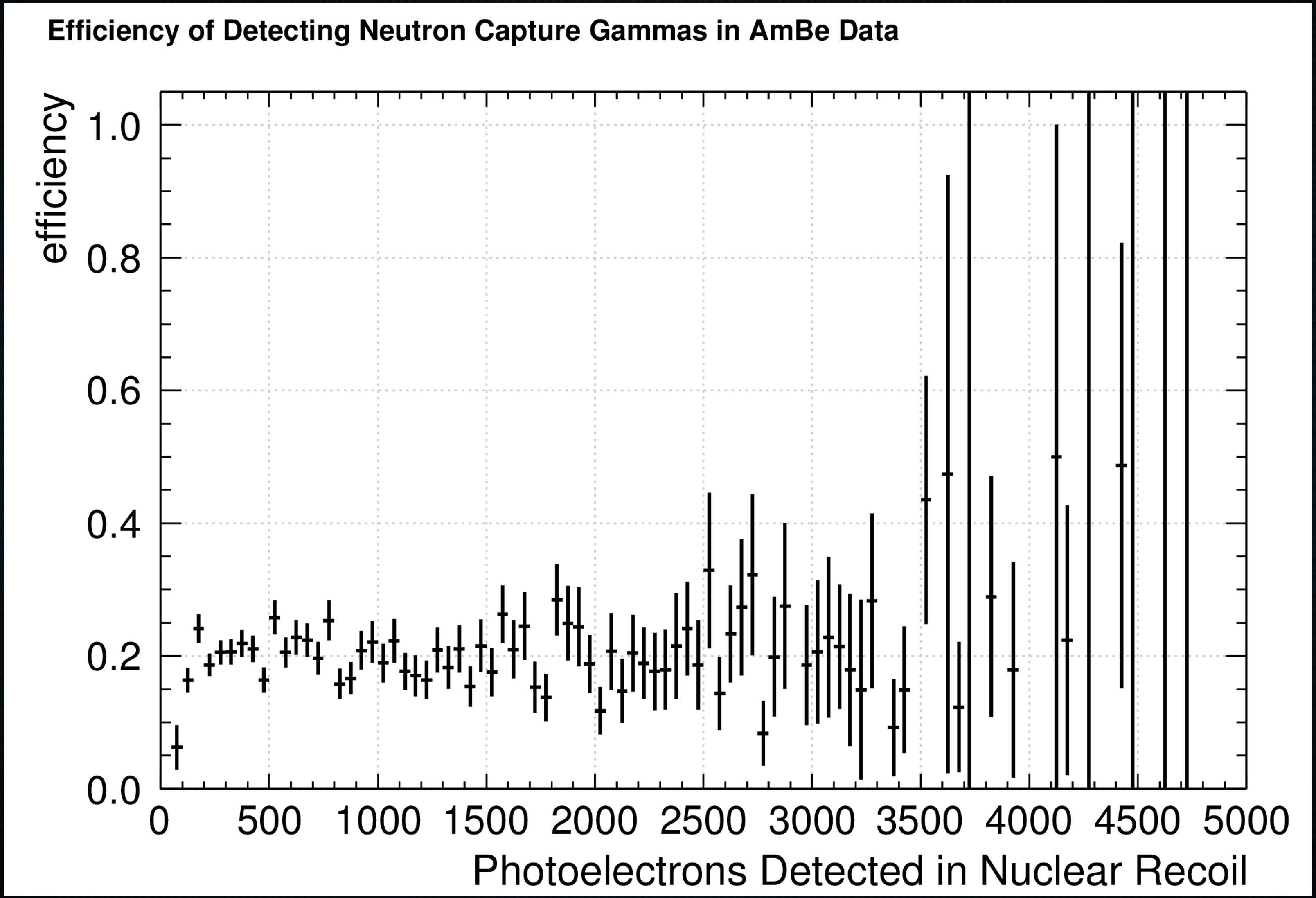


AmBe Calibration: Detect NR-ER Coincidence was 19.3% Efficiency



In Situ Neutron Search: Saw no neutron captures

- Looked at 109 days of data in DEAP-3600
- Saw 0 NR-ER pairs
  - Require: NR above 11 keVee
  - Require: ER abve 1.9 MeV
- Expected 1.4 false coincidences

Upper limit on neutron event rate consistent with prediction

Feldman-Cousins upper limit (90% C.L.):
< 25.5 n/year scatter in LAr above 11 keVee

Consistent with NeuCBOT prediction of 18.6 n/year!

Conclusion

- We have developed a new tool for calculating (α,n) yields in arbitrary materials
  - NeuCBOT: https://github.com/shawest/neucbot
- Validated against measured yields and SOURCES-4C calculations
- Predict ~18.6 n/year in DEAP-3600
- *In situ* limits constrain rate of neutrons in LAr to < 25.5 n/year
  - Consistent with NeuCBOT predictions

End

AmBe Calibration: Capture signals reliably follow neutrons by 1 ms