Neural Networks for Experimental Nuclear Astrophysics

The $^{17}O(p,\gamma)^{18}F$ Resonance at 65 keV as a Test Case

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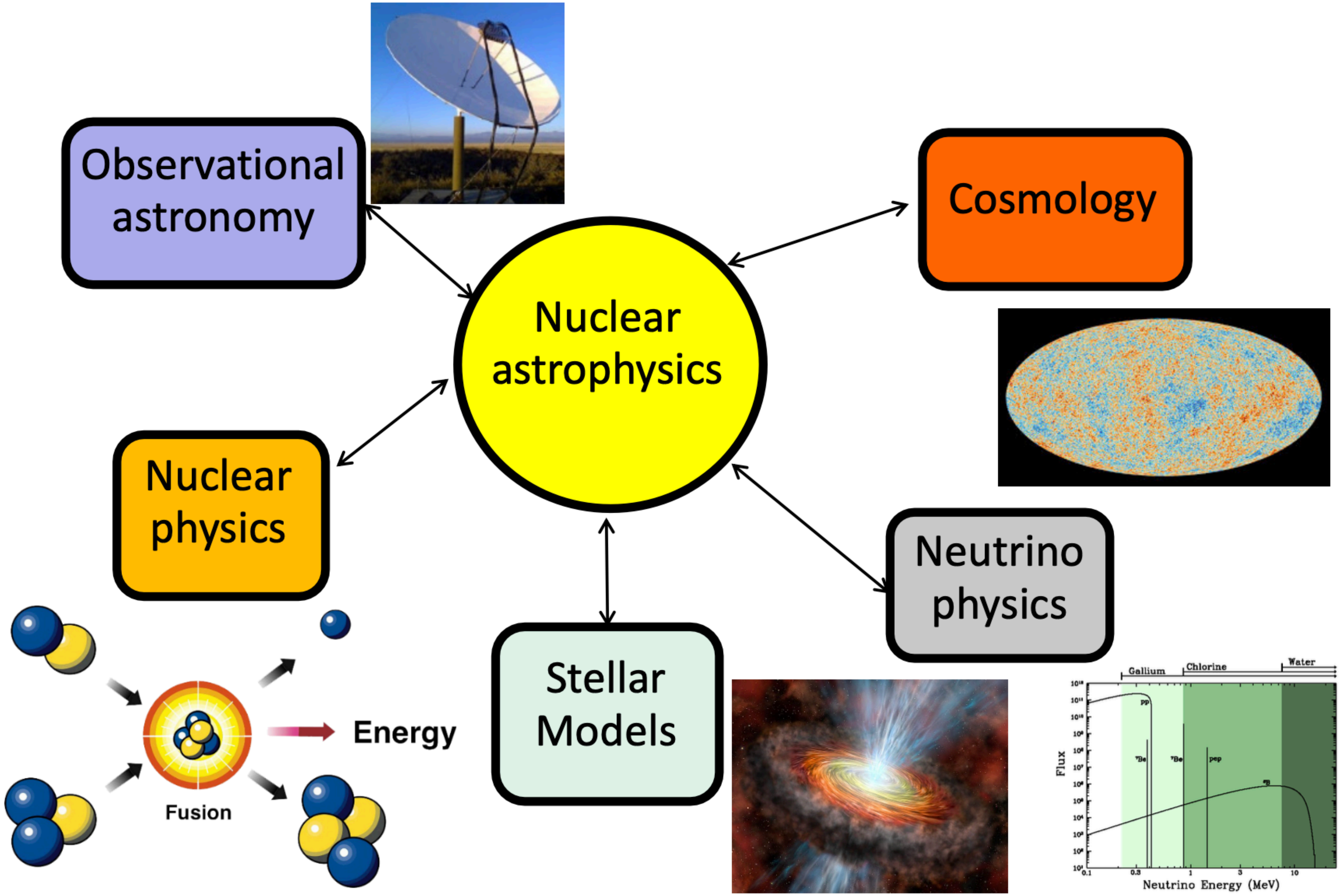
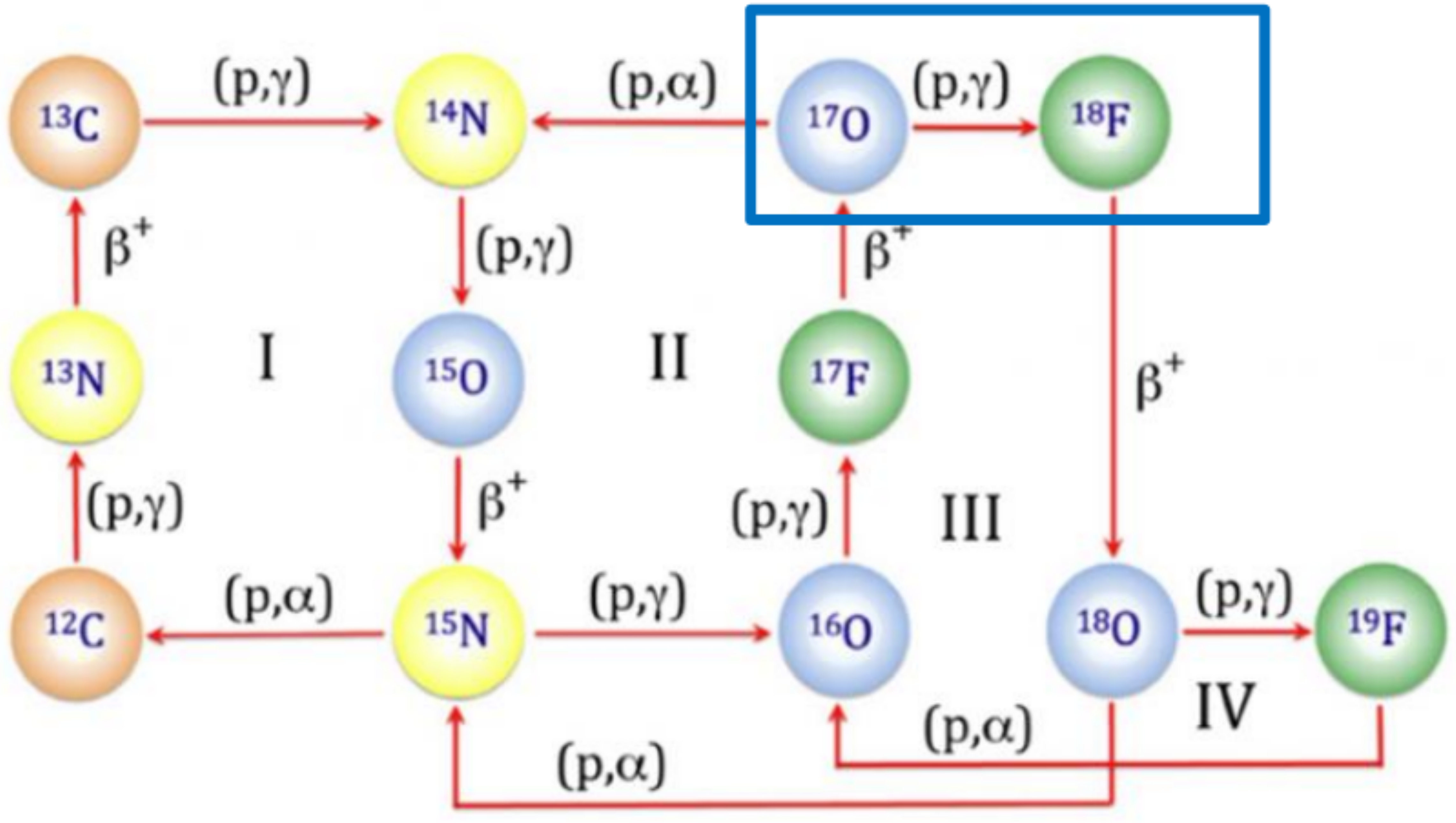
Nuclear Astrophysics



Astrophysical Motivation

- The **$^{17}O(p,\gamma)^{18}F$** reaction takes part in the **CNO cycle**
- The CNO cycle is the predominant **energy production mechanism** for heavy stars **($M > 1.3\ M_{\odot}$)**
- The reaction rates of the CNO cycles determines the **abundances of elements inside the stellar core**



CNO Cycle

Measuring Reaction Cross Sections → **Describing Stellar Evolution and Nucleosynthesis**

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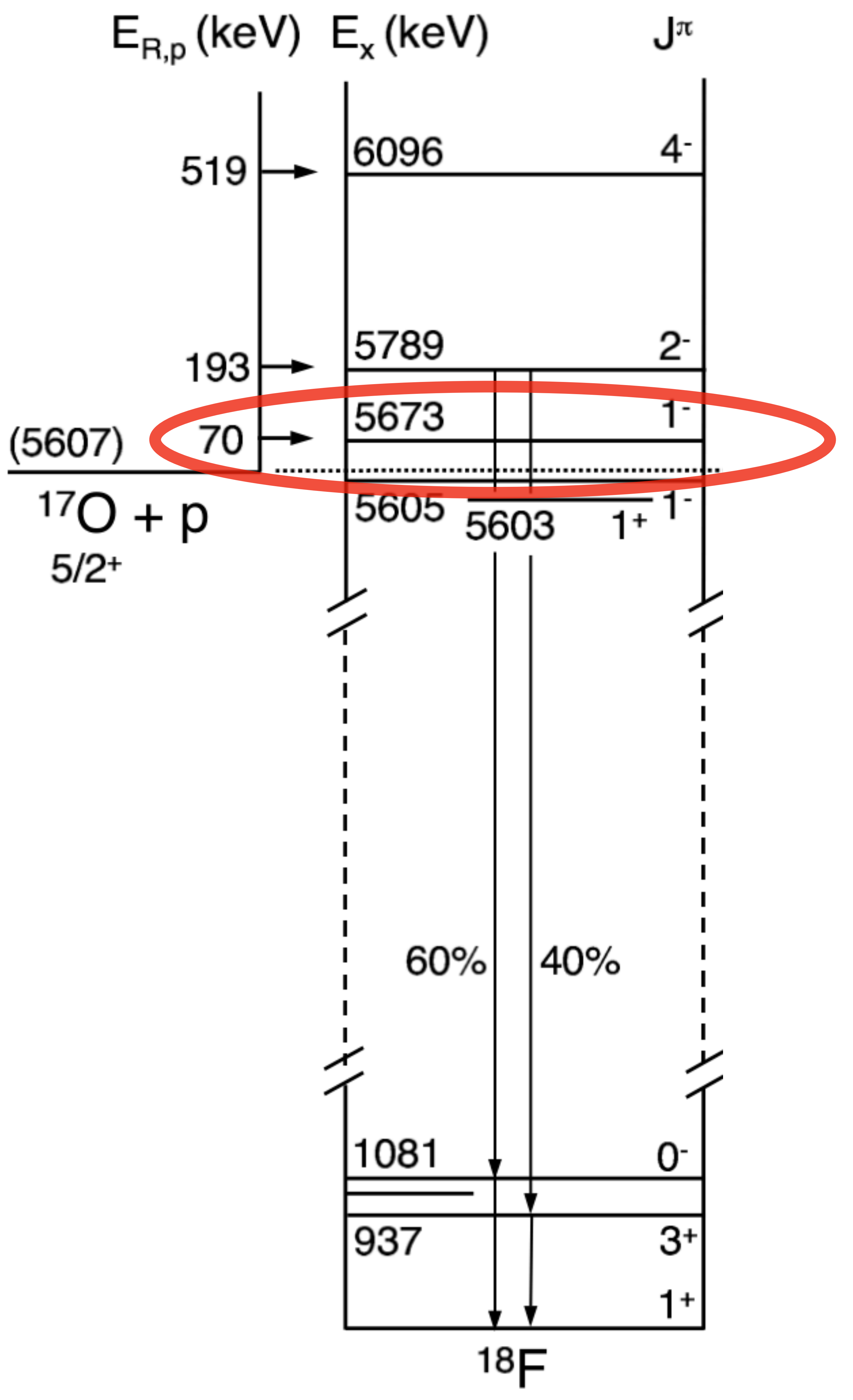
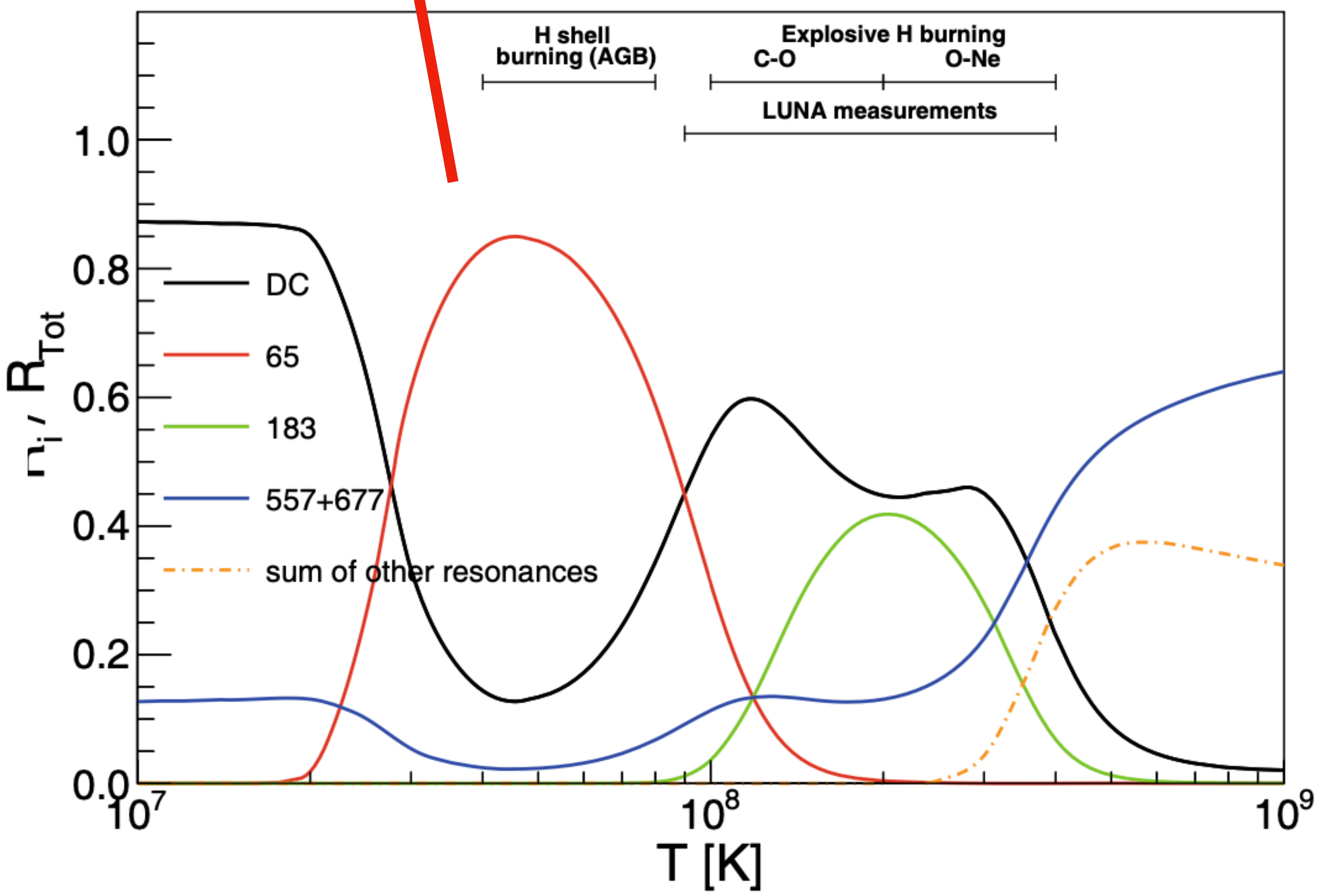
$^{17}O(p,\gamma)^{18}F$ Reaction



The **reaction rate** in the range of interest is **dominated** by the **resonance at 65 keV!**

Reaction Rate



65 keV Resonance

No direct measurements available

Estimated strength of the resonance: **$\omega\gamma$ = (1.6 ± 0.3) x 10^{-11} eV** ($\omega\gamma$ ~ Cross Section)

→ Only **1 count per day** (considering a proton current of 100 μA)

What we need:

- High detection efficiency (**~ 50%**)
- Environment with exceptional background reduction (< 1 event / day)
- Optimal signal / noise ratio

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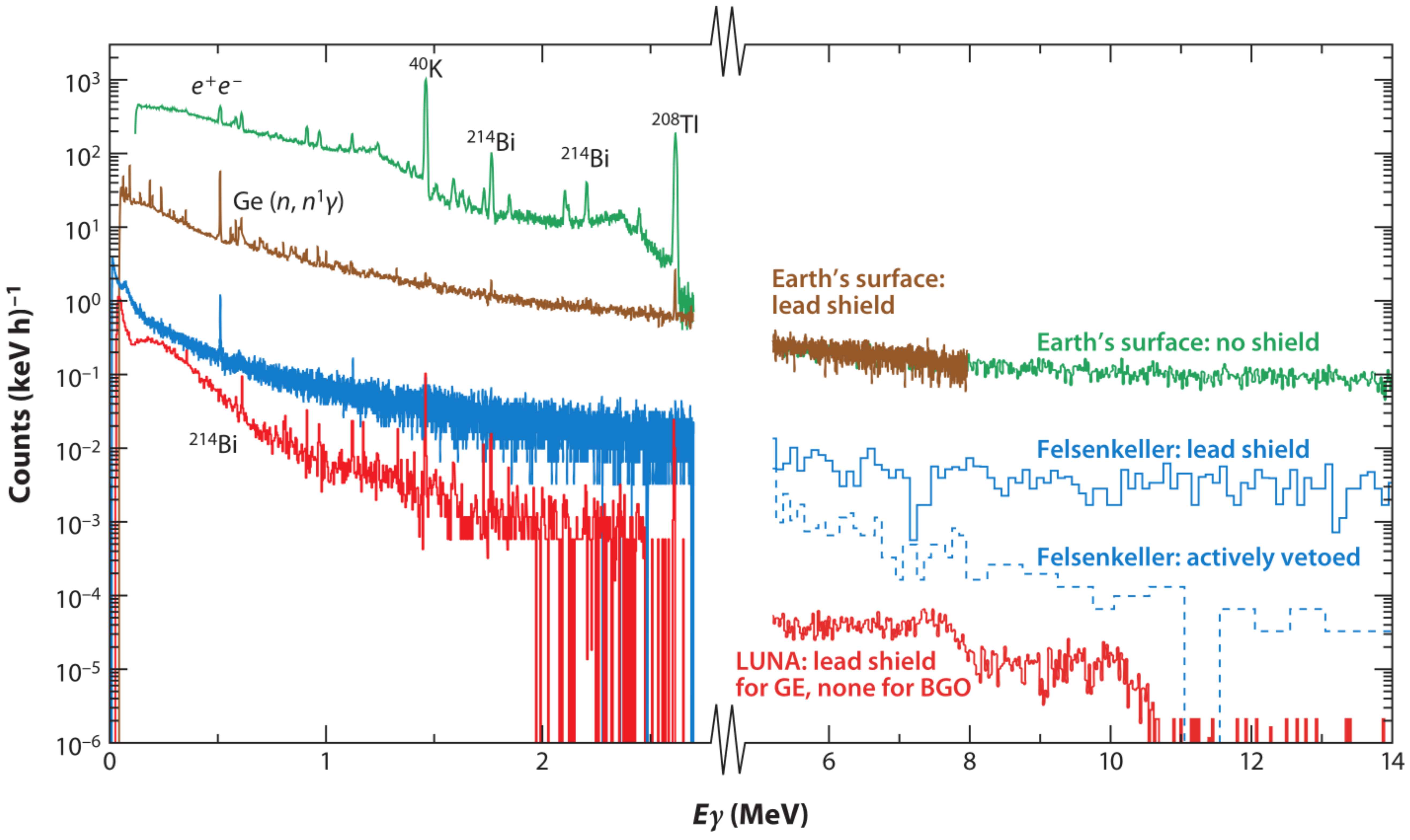
Laboratory for Underground Nuclear Astrophysics

- Located at **LNGS** facility under the **Gran Sasso mountain** in Abruzzo, Italy
- The cosmic ray flux reduced by **six orders of magnitude**



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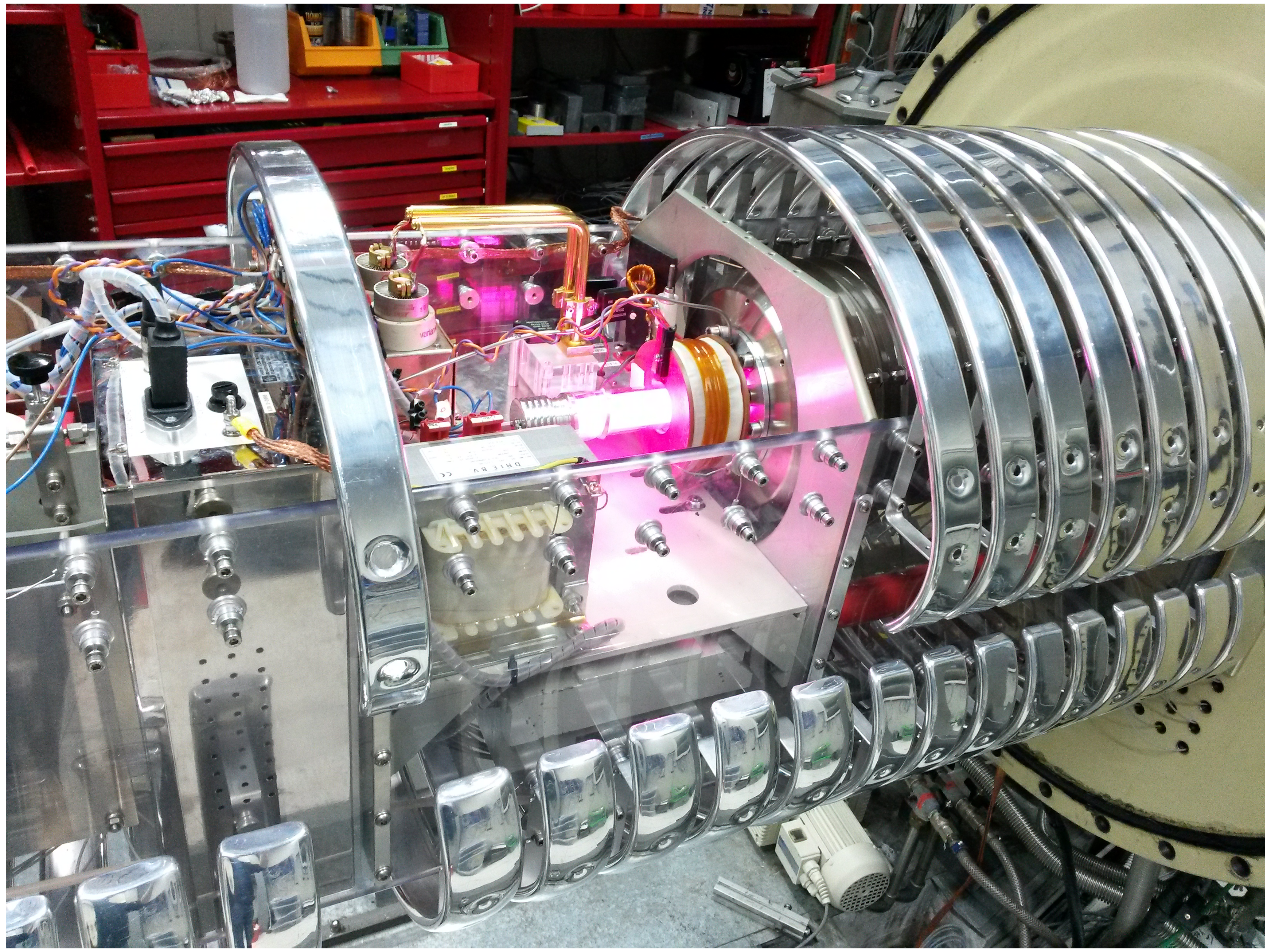
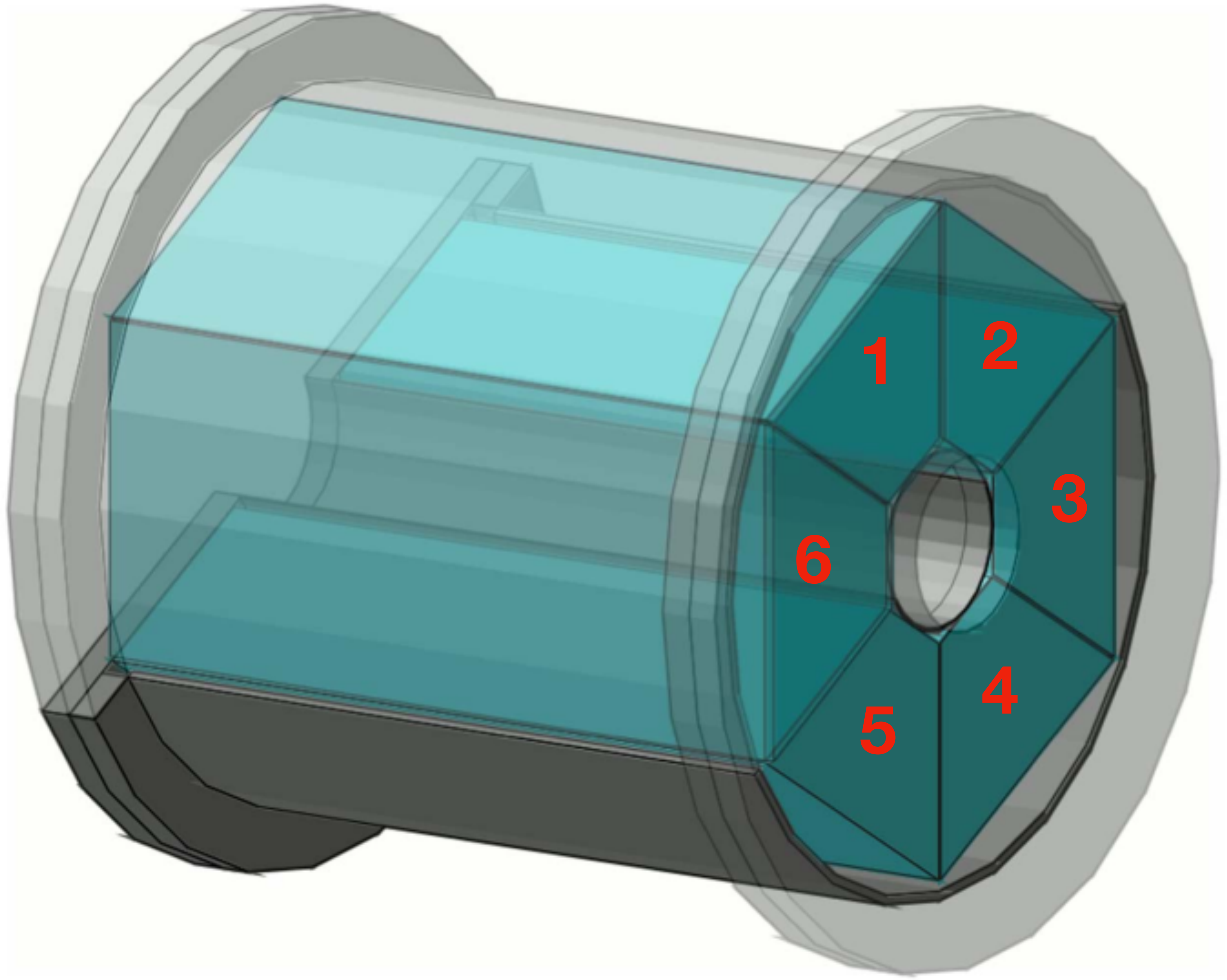
Experimental Setup - BGO Detector

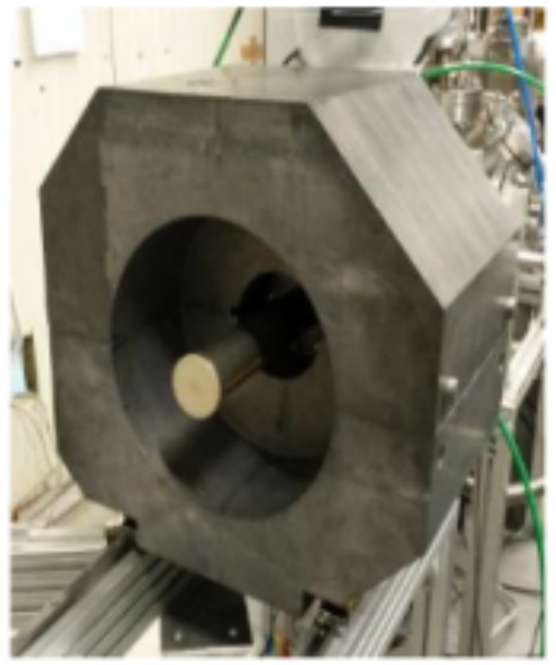
LUNA 400kV Accelerator

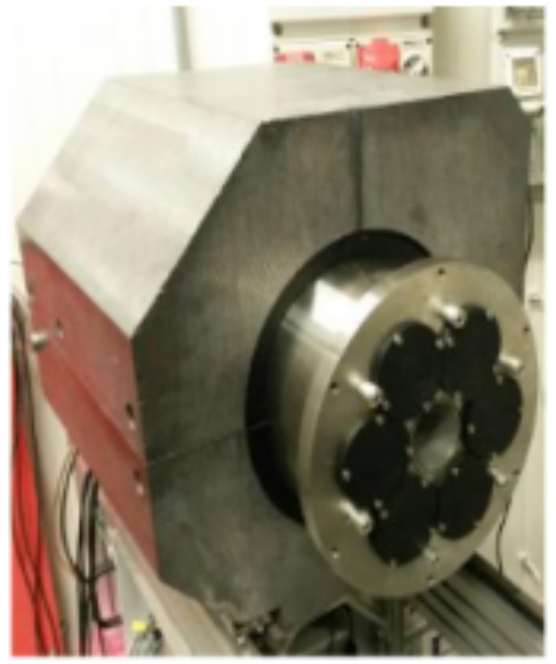


- *p* beam up to **400 μA**
- **E_p = 50 - 400 keV**

BGO Detector







- Almost **4π geometry**
- Segmented in **6 different crystals**

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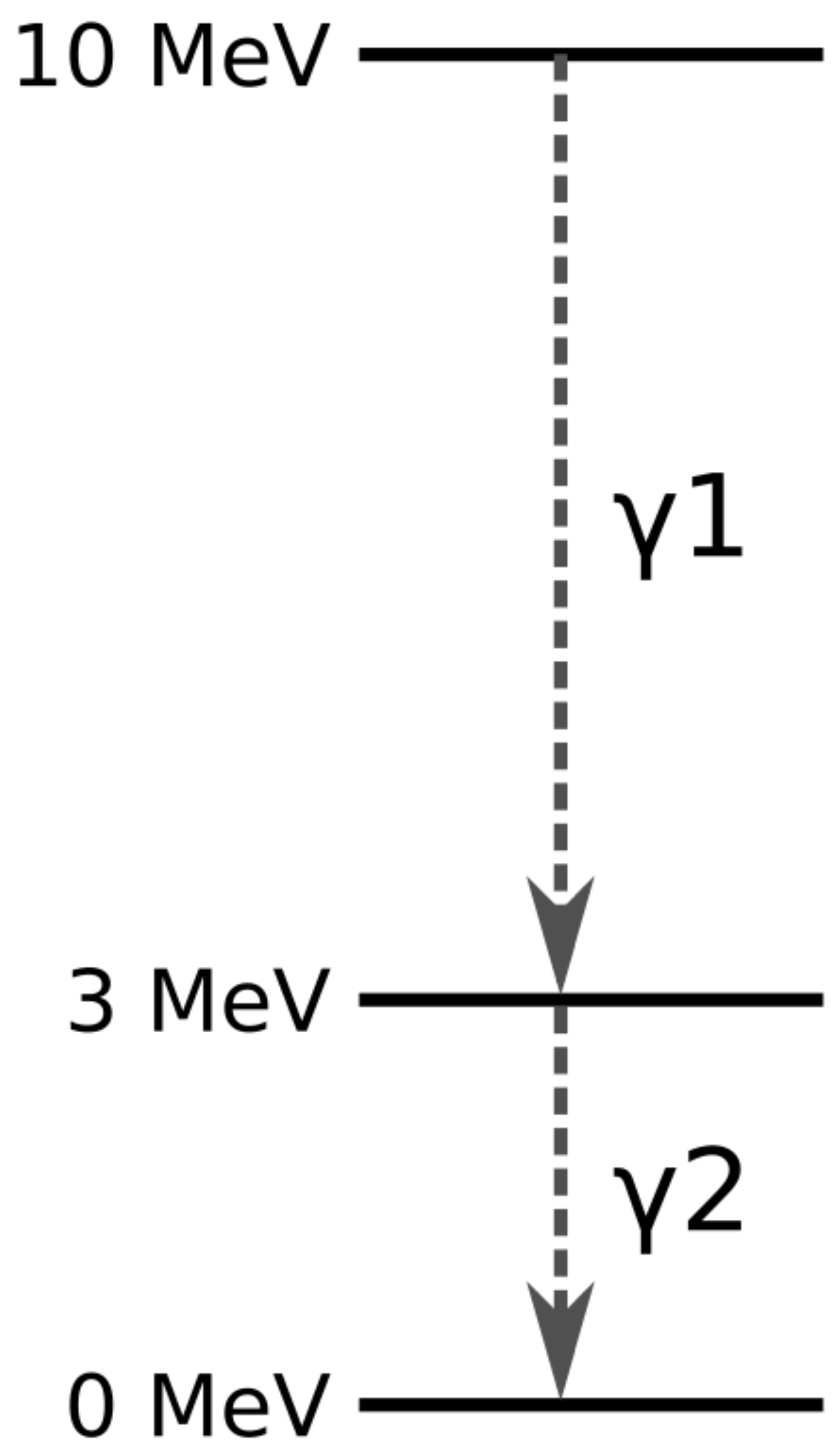
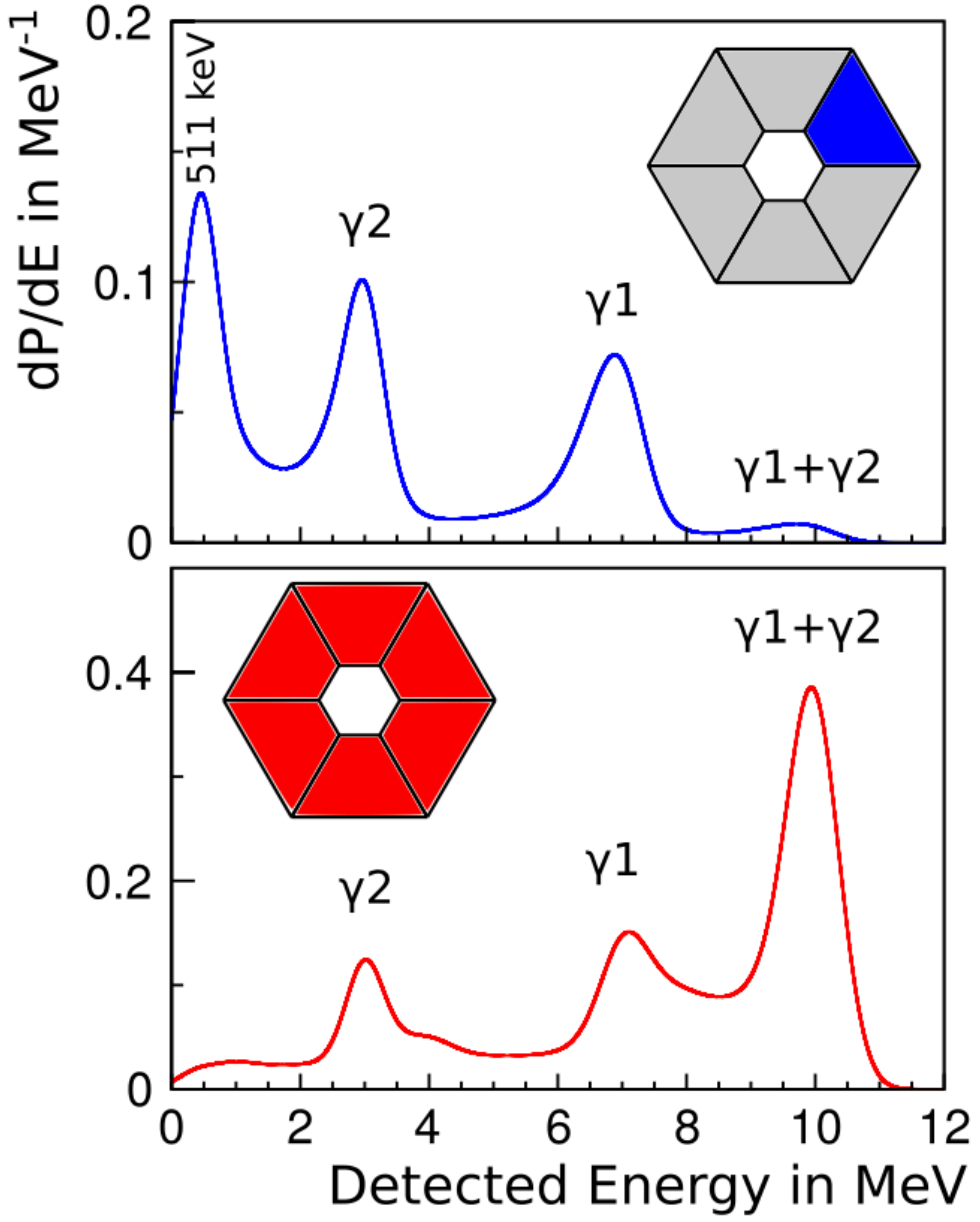
Total Absorption Spectroscopy

Idea

1. Detect **all the γ-rays** in coincidence
2. Construct the **sum γ-peak** by summing all the crystals
3. **Count the events** inside the sum γ-peak
4. Calculate the **cross section**





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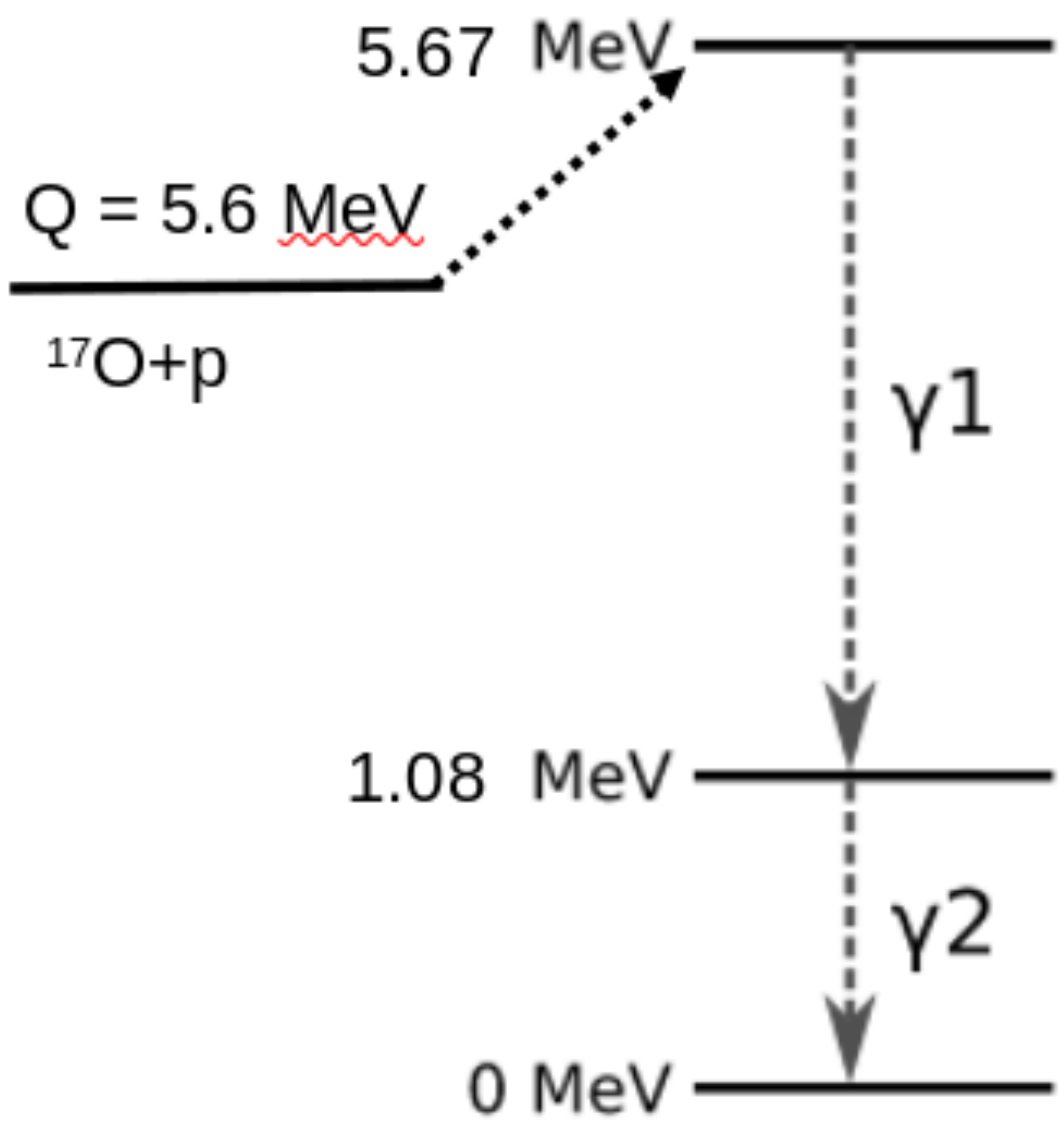
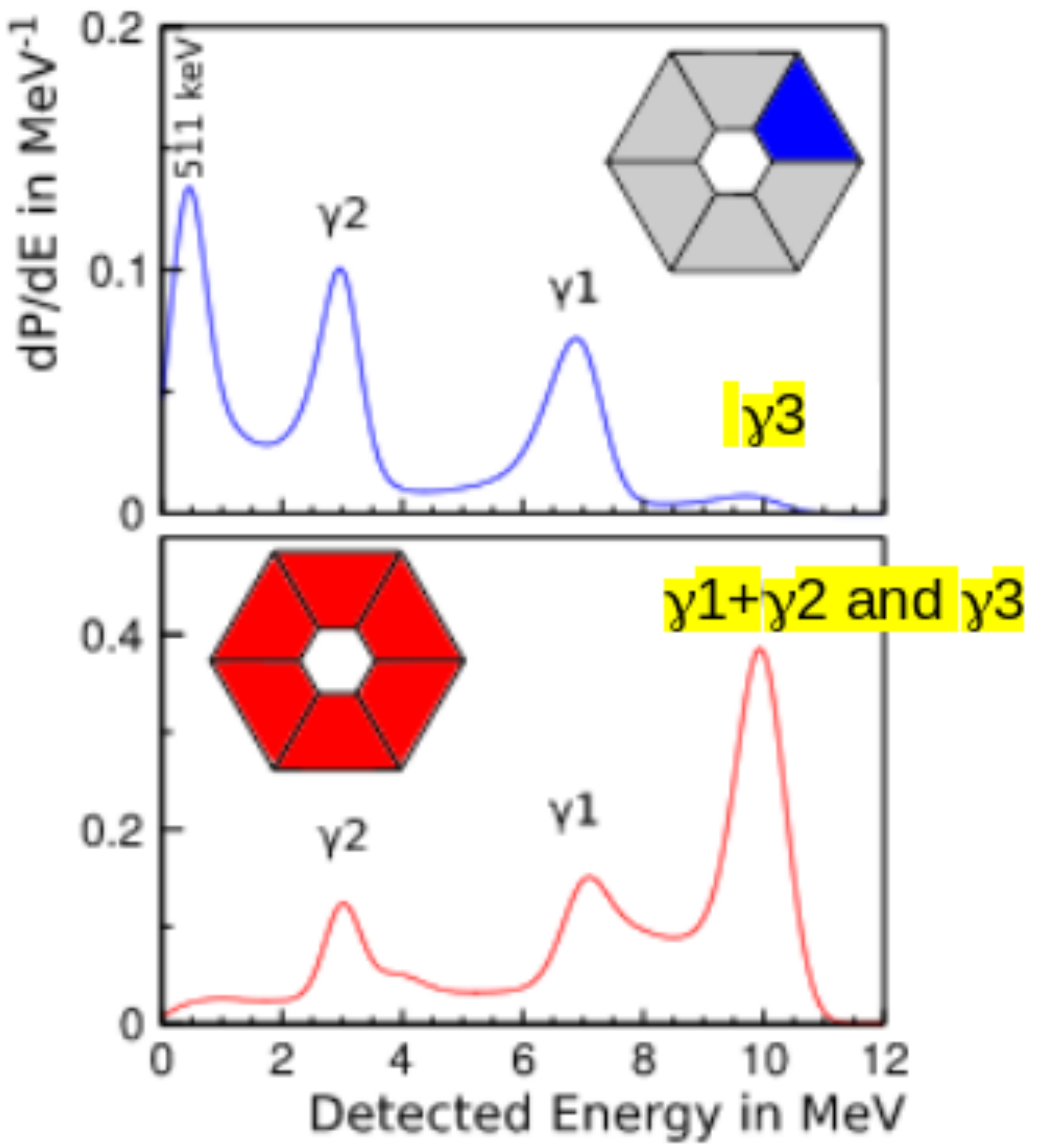
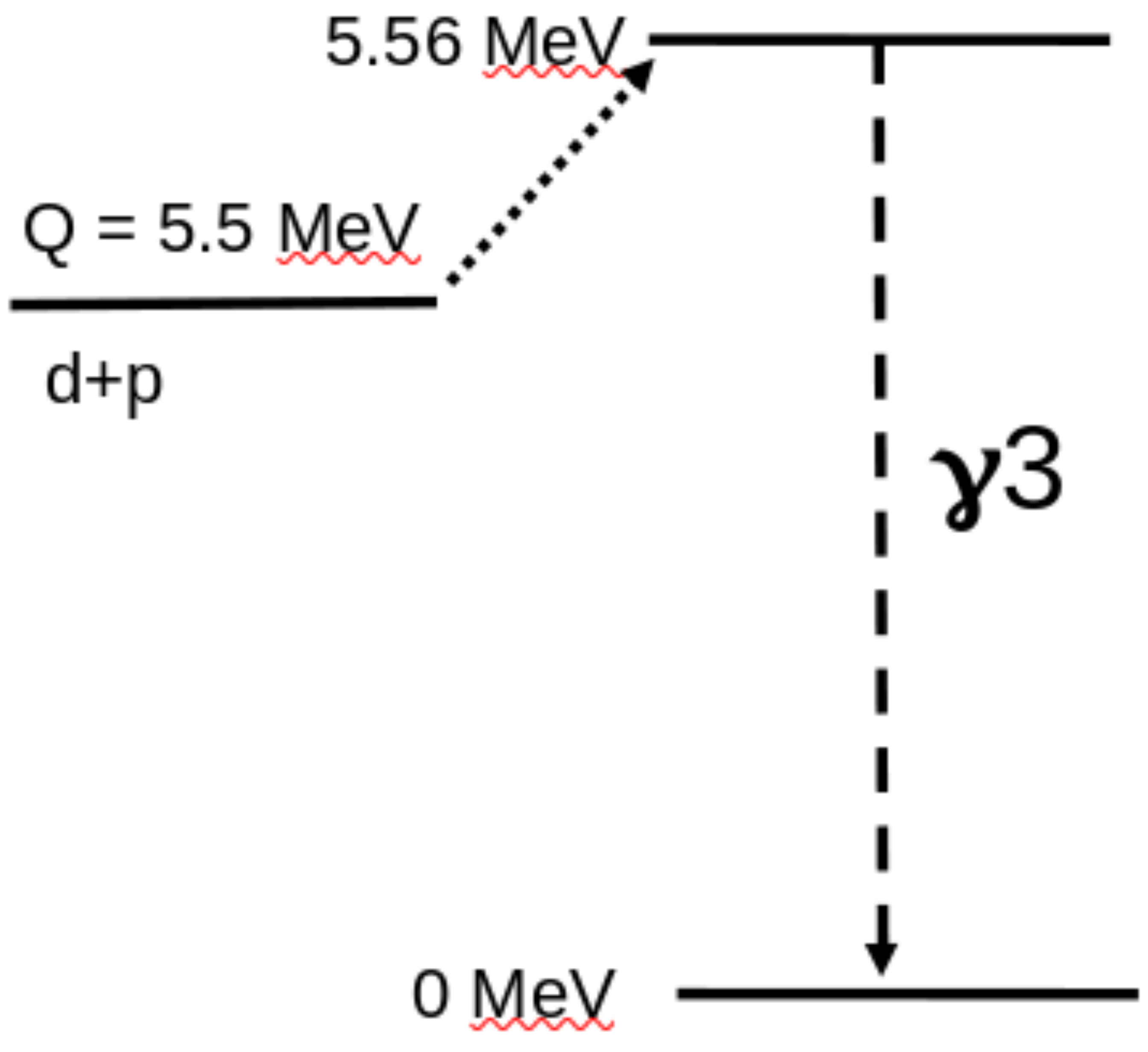
Deuteron Background

Problem: Ta backing (where **^{17}O is evaporated**) contains **deuterons**…







Classic: gating the spectrum on the two γ-rays (thus reducing statistics)

New: use Neural Networks to distinguish between ^{17}O + p and p + d events

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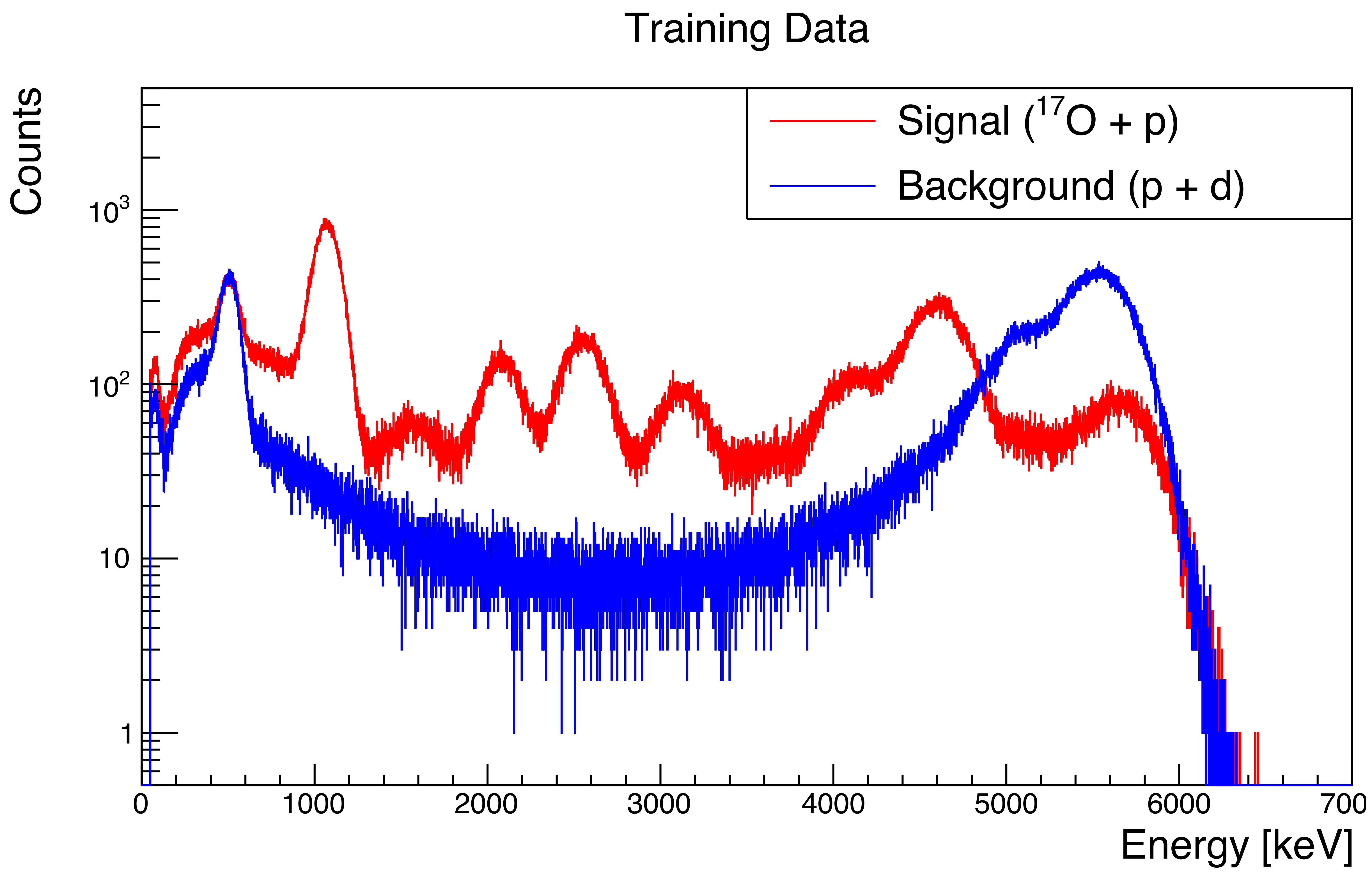
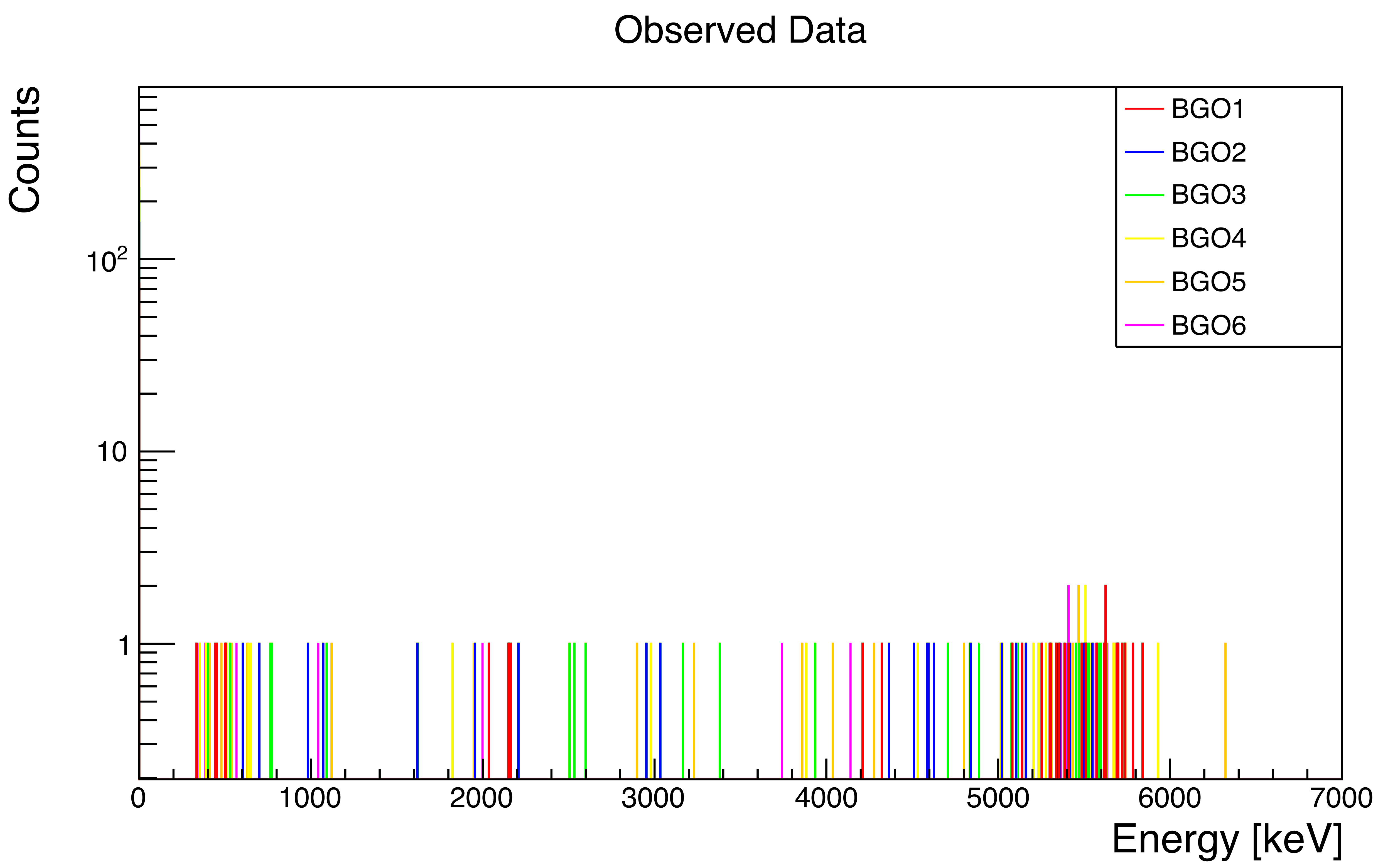
Training and Observed Data

Geant4 simulations used as training data (**event by event**):

- Validated with calibration sources (**J. Phys. G: Nucl. Part. Phys. 50 045201**)
- Added random gain shifts to reproduce the BGO drifts





Simple Neural Network Architecture

Classification

The accuracy of the classifier is defined as:

Accuracy = P(True Positives) + P(True Negatives)

In order to extract the cross section it is important to estimate the **selection efficiency**, i.e. how many events we classify as signals respect the total signals:

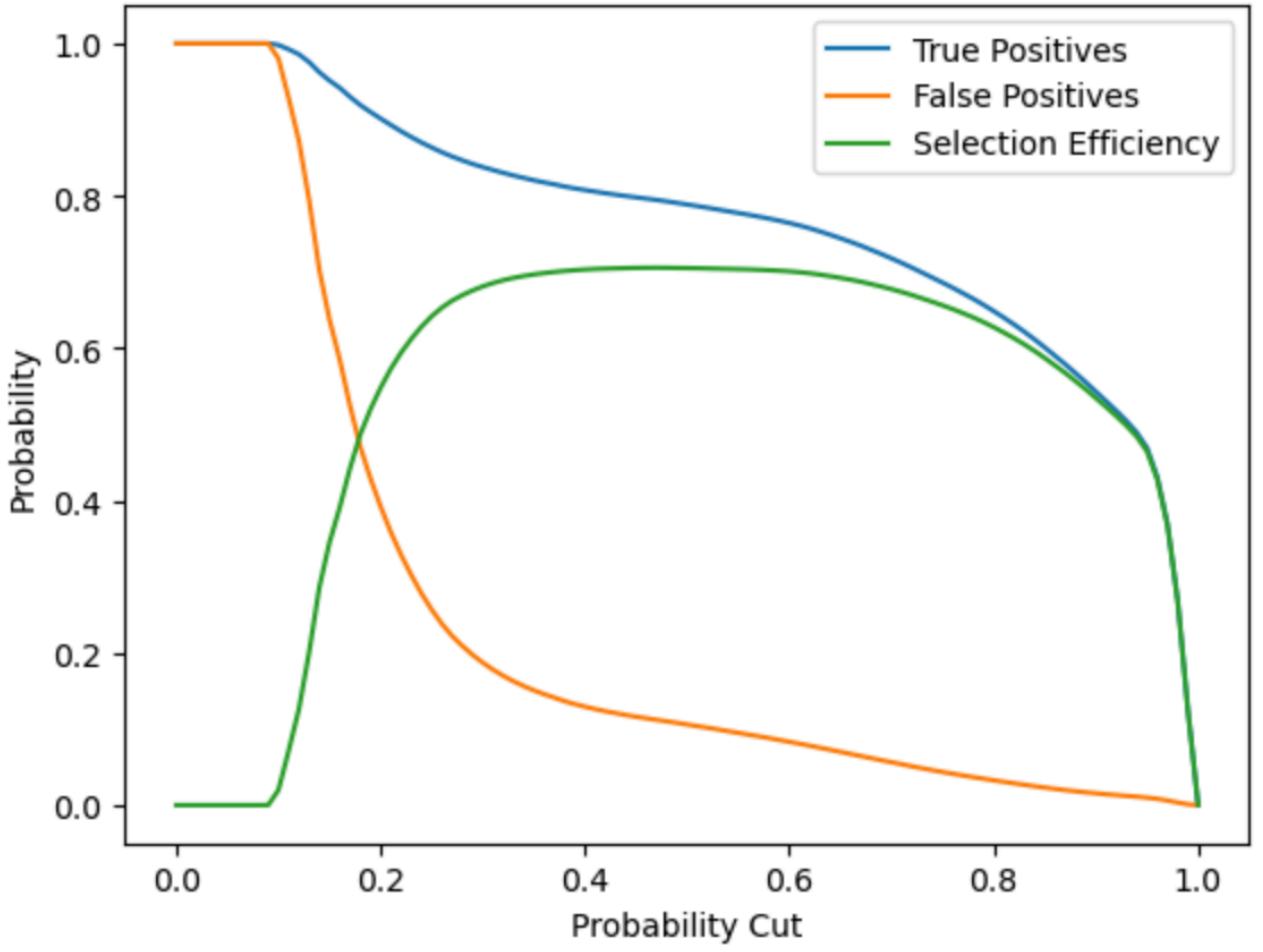
Selection Efficiency = [1 - P(False Positives)] x P(True Positives)

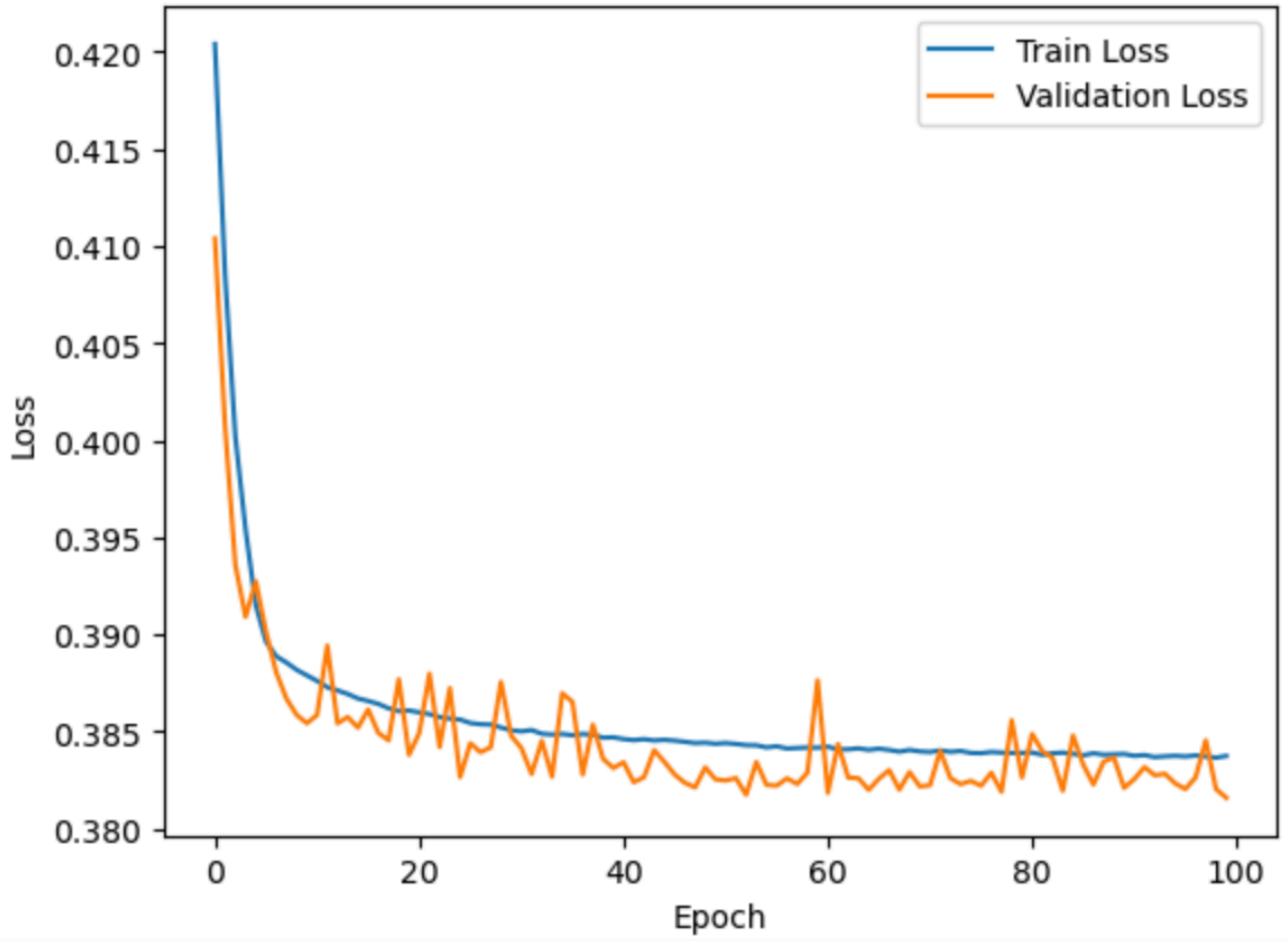
↓

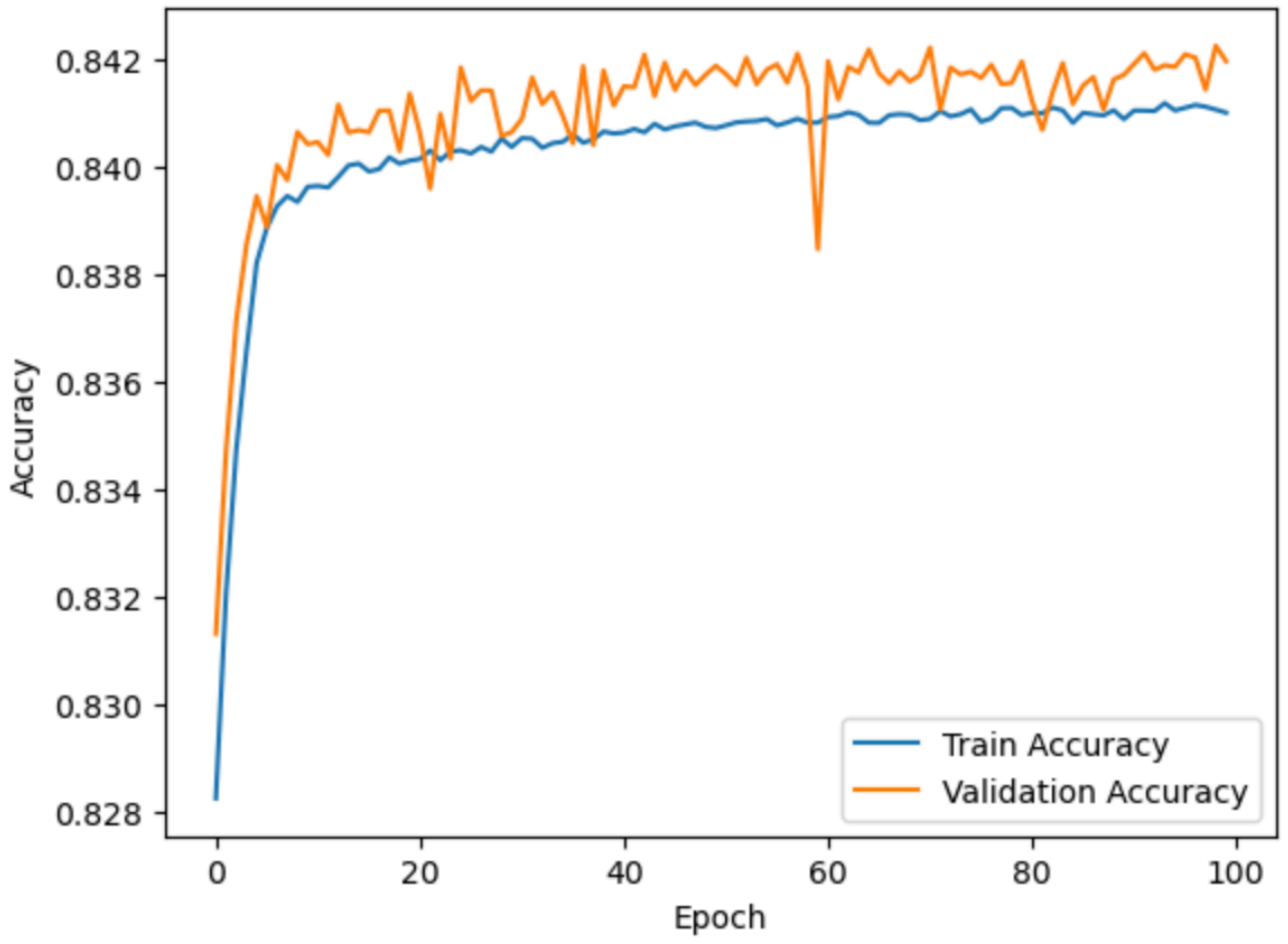
Reaction Yield = Number of Signals / Selection Efficiency

Performance (1)

- The network immediately learns the features
- The probability of **True Positives** and **False Positives** depends on the **probability cut**
- For a cut at **0.5** we obtain an **accuracy** of **84%** and an **selection efficiency** of **70%**

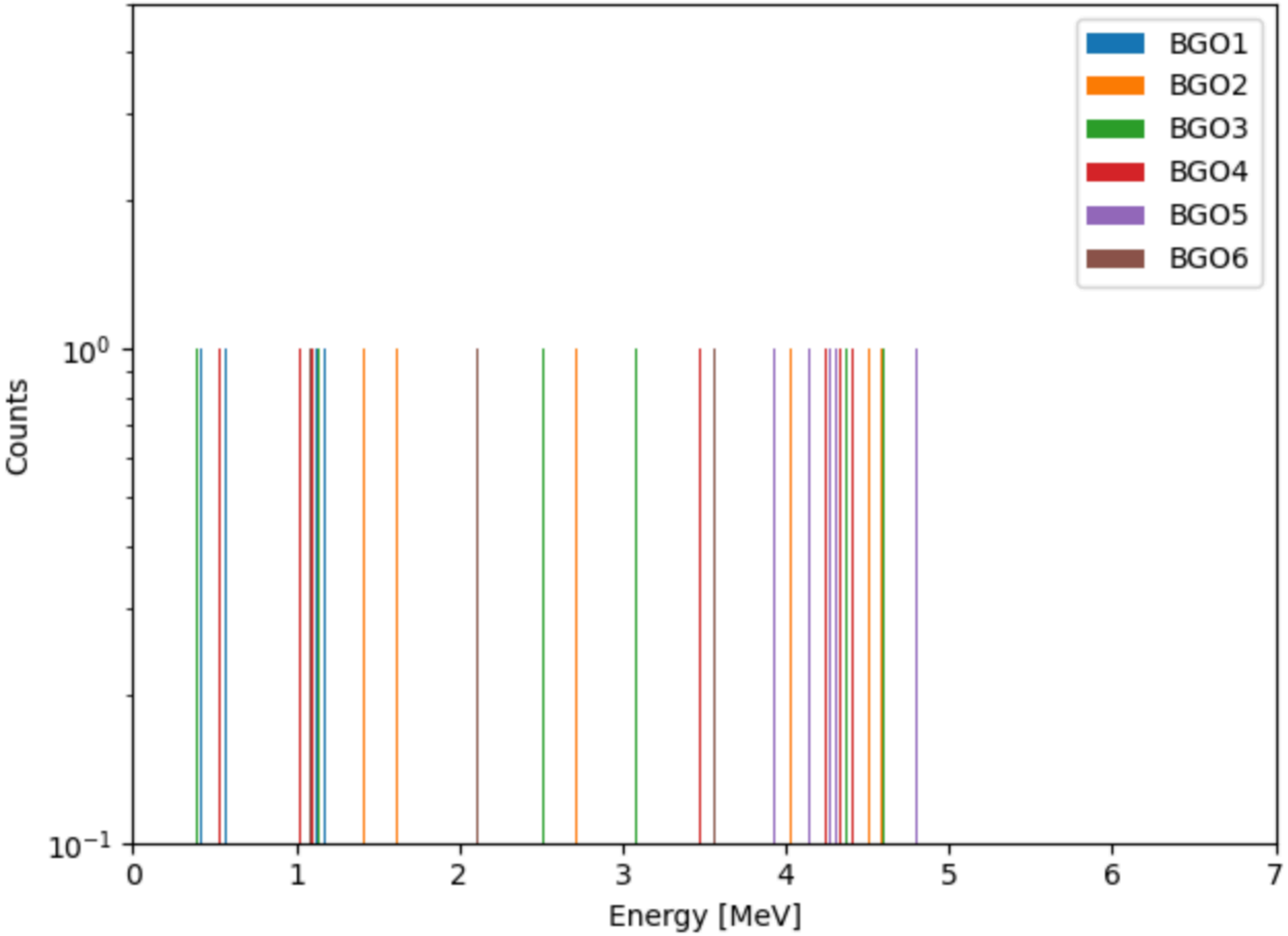




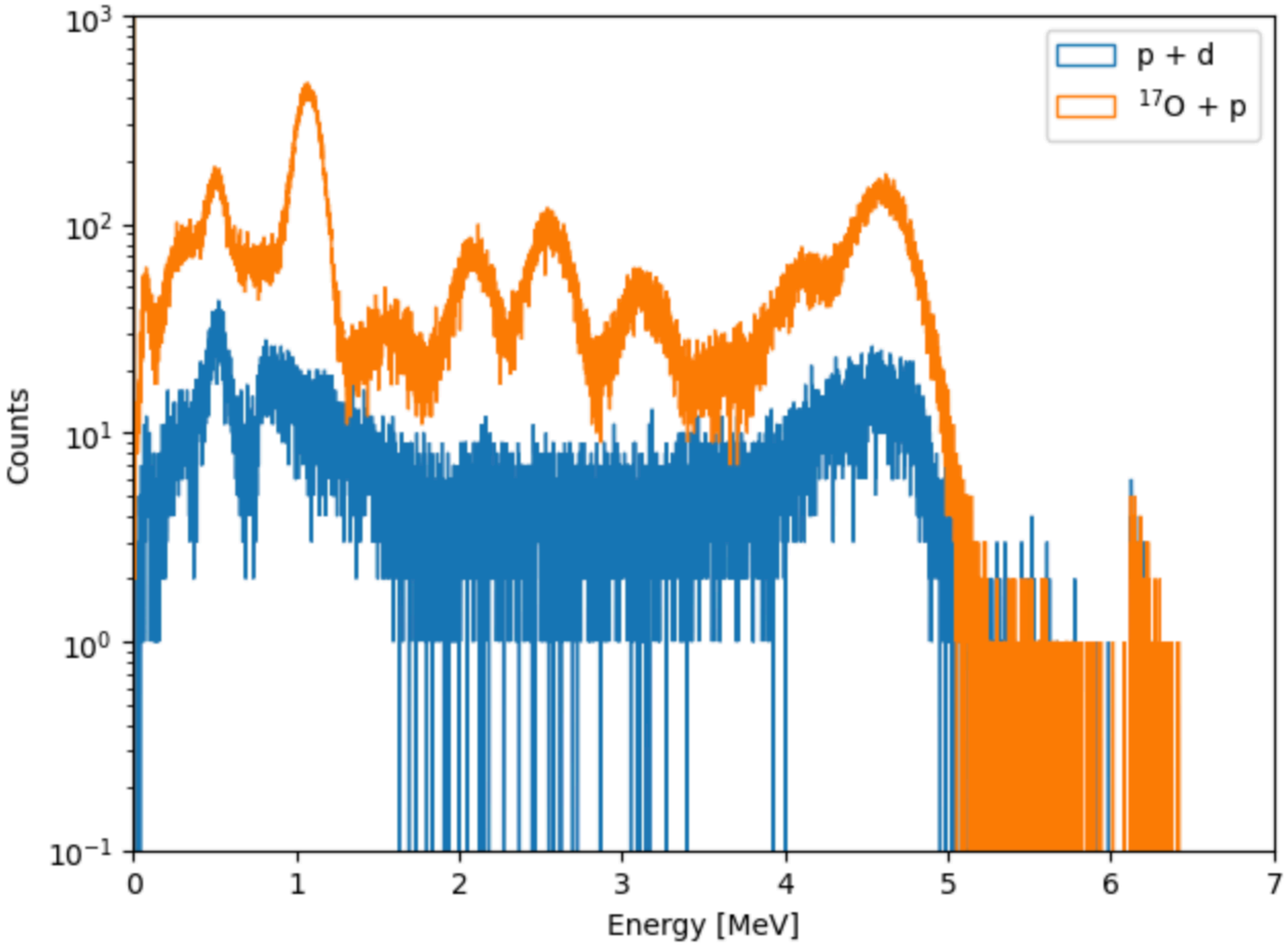


Performance (2)

True Positive Observed - All Crystals



True Positive Simulated - One Crystal



Results

Target	Counts (Classic)	Counts (NN)	Reaction Yield (Classic)	Reaction Yield (NN)
T24	41	69	102	98
T28	15	30	39	42
T44	25	50	62	71
Total	81 ± 9	149 ± 12	**202 ± 22**	**212 ± 17**

Classic Selection Efficiency = **40 %**

Neural Network Selection Efficiency = **70 %**

Neural Network approach permits to **increase the statistics** and **reduce the final error**!

Conclusions

- Nuclear Astrophysics usually deals with **extremely low counting statistics**
- A simple **Neural Networks** can allow to obtain more **efficient cuts on the data**
- The **$^{17}O(p,\gamma)^{18}F$** is the perfect example for this
- **Future Prospective:** train the NN directly on the observed γ-spectra

Thank you for attention!

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LUNA Collaboration