UNIVERSITÀ DEGLI STUDI DI PADOVA

Investigating Deuterium destruction in BBN with the Felsenkeller Accelerator

Supervisor: Prof. Antonio Caciolli, University of Padova & INFN, Padova
Co Supervisor: Dr. Eliana Masha, HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Aravind Remesan Sreekala
MSc Astrophysics & Cosmology
University of Padova

20th September, 2023

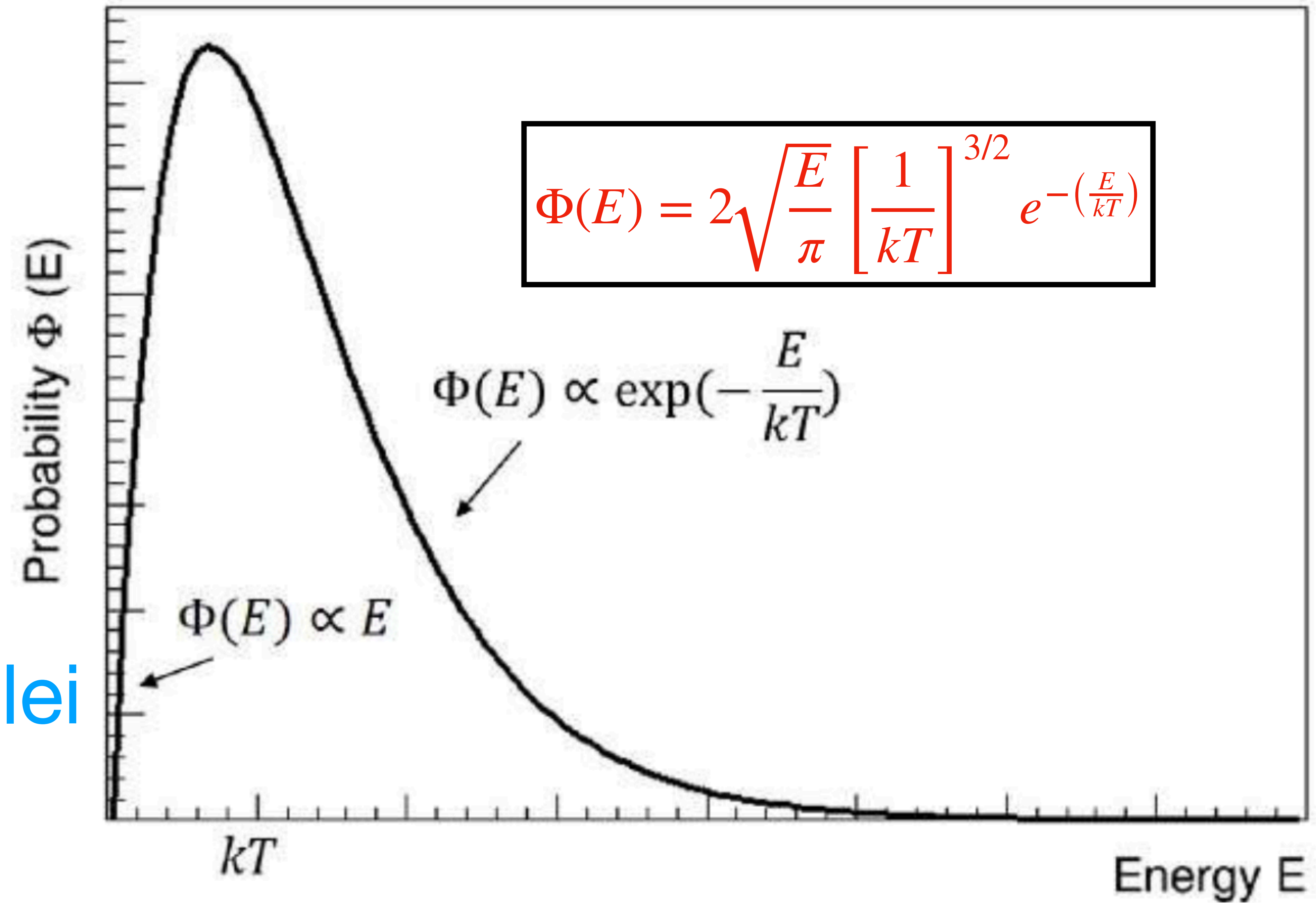
Thermonuclear Reactions

Example: $x + A \rightarrow B + y$

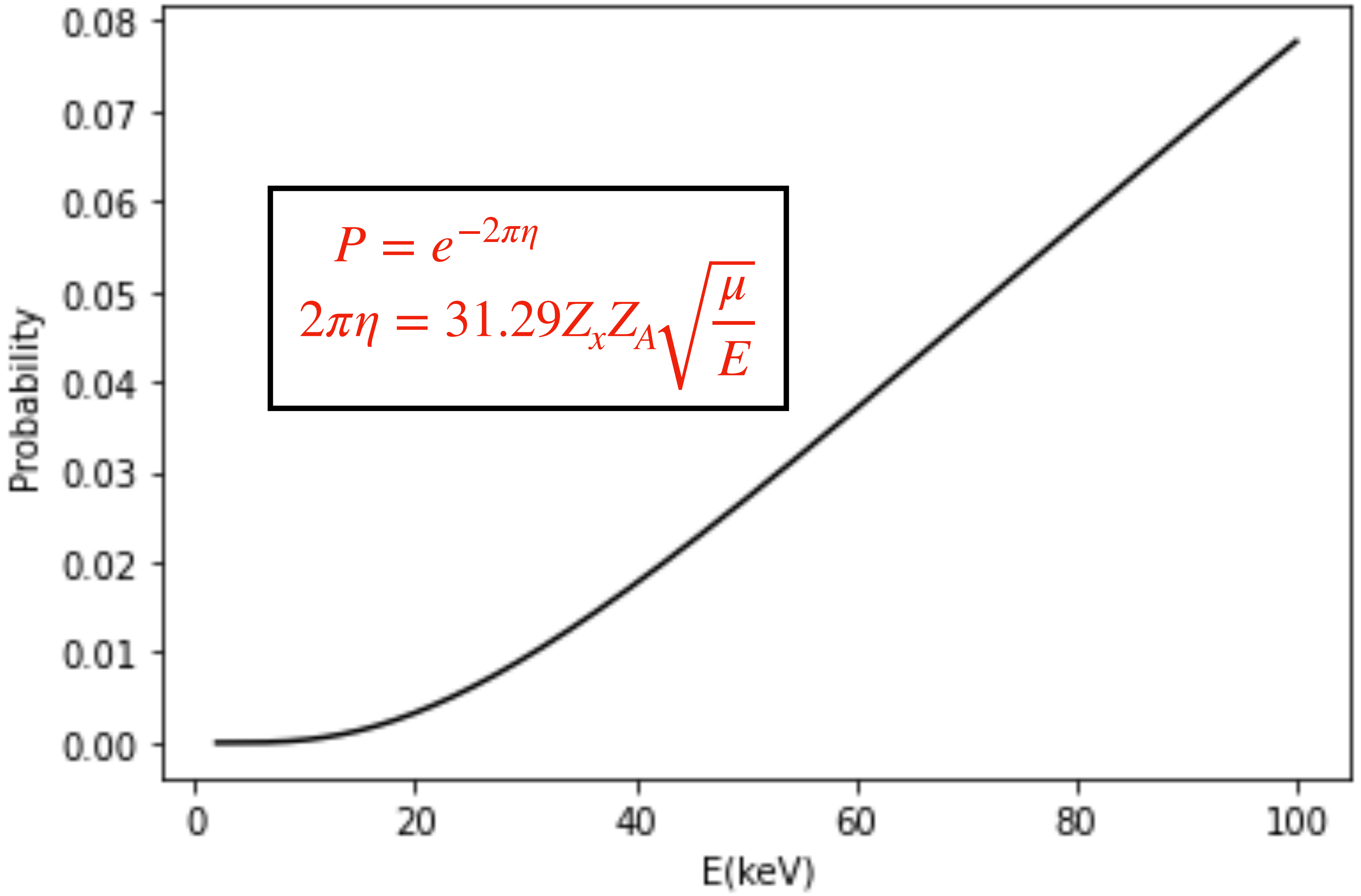
Rate, $r = v\sigma(v)N_x N_A$

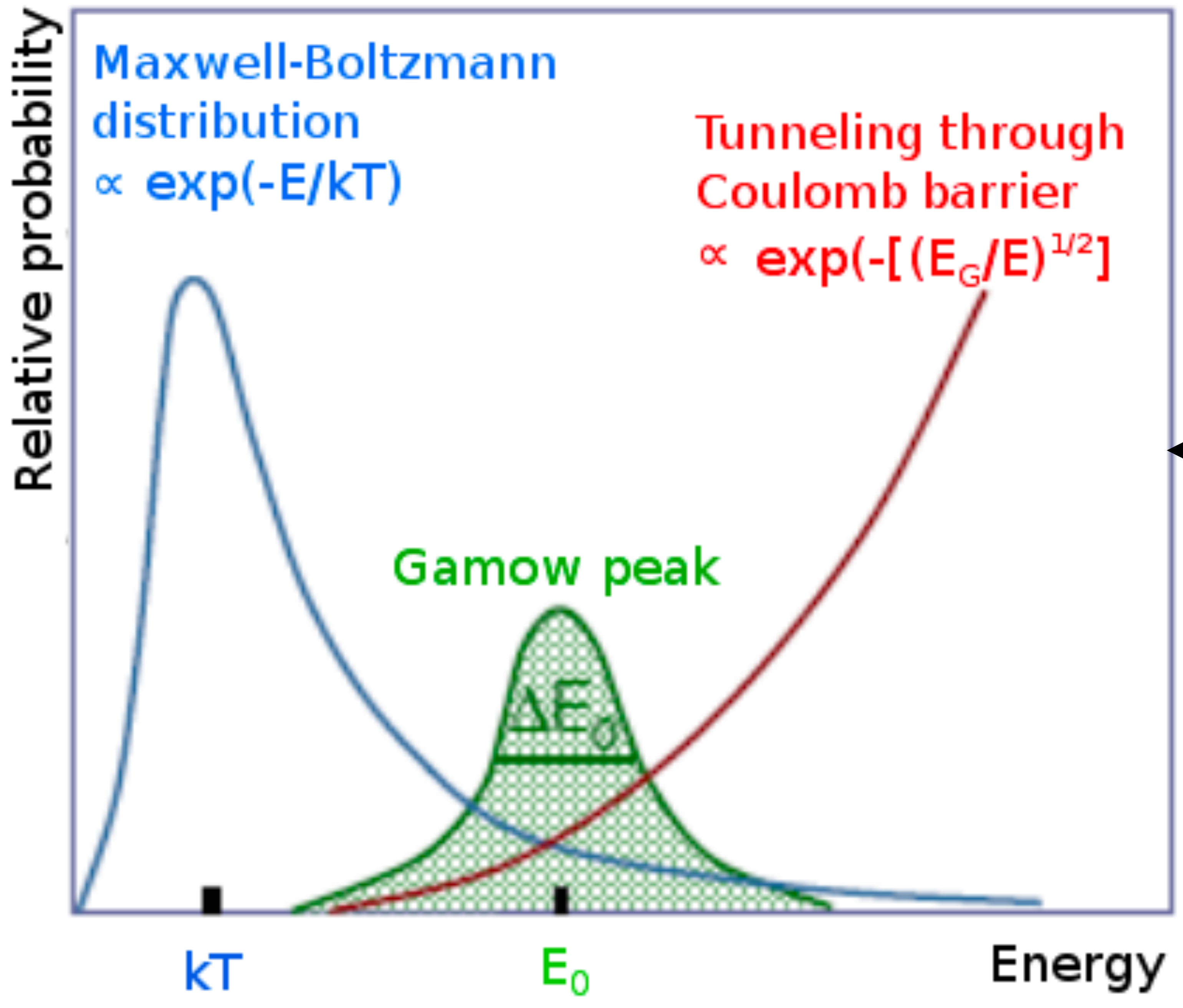
Reaction Cross Section

1) Energy of incident nuclei



2) Tunnelling of Coulomb barrier





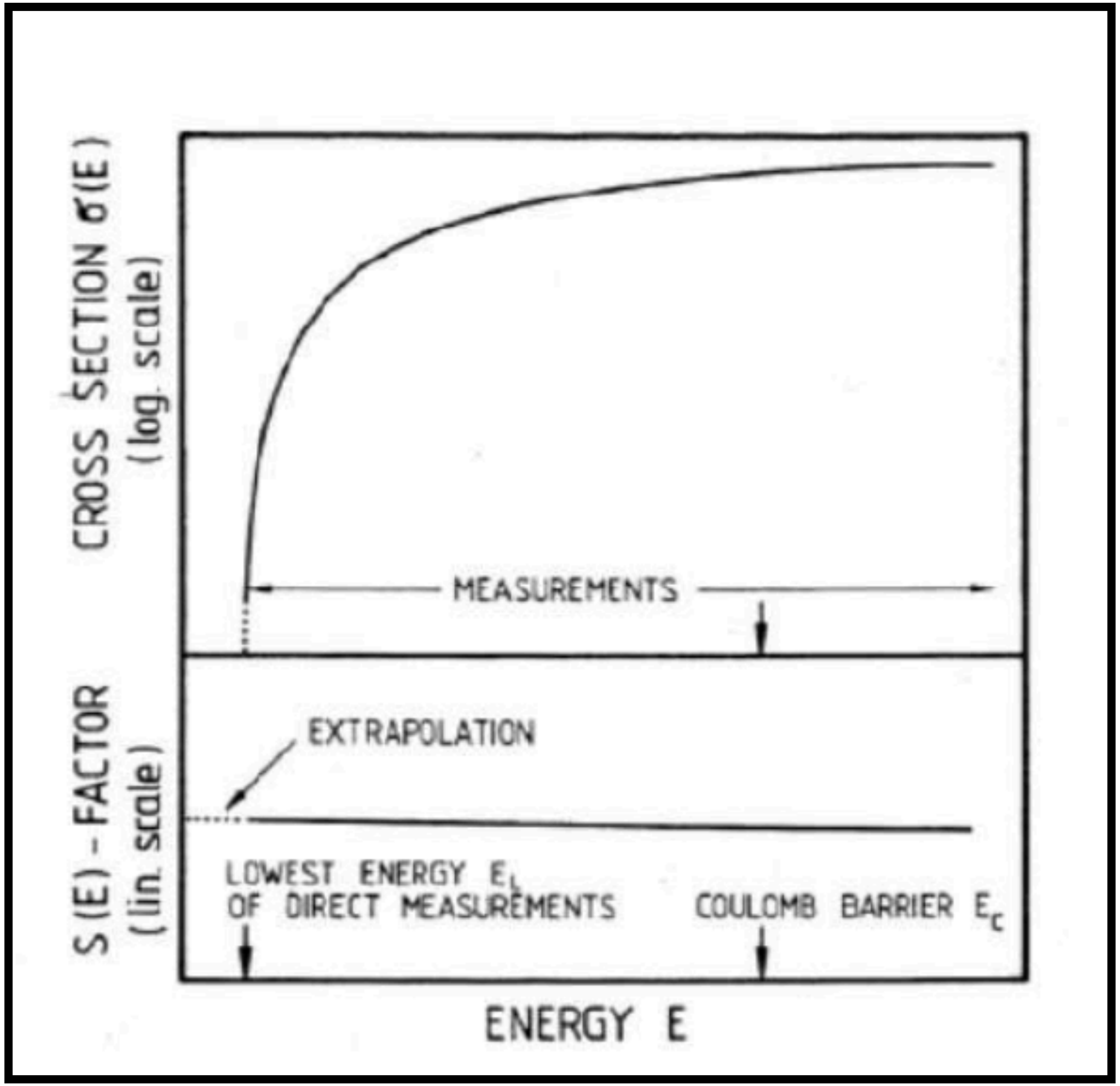
$E_O \gg kT$

Cross-Section to S-Factor?

- **Astrophysical S-Factor S(E)**

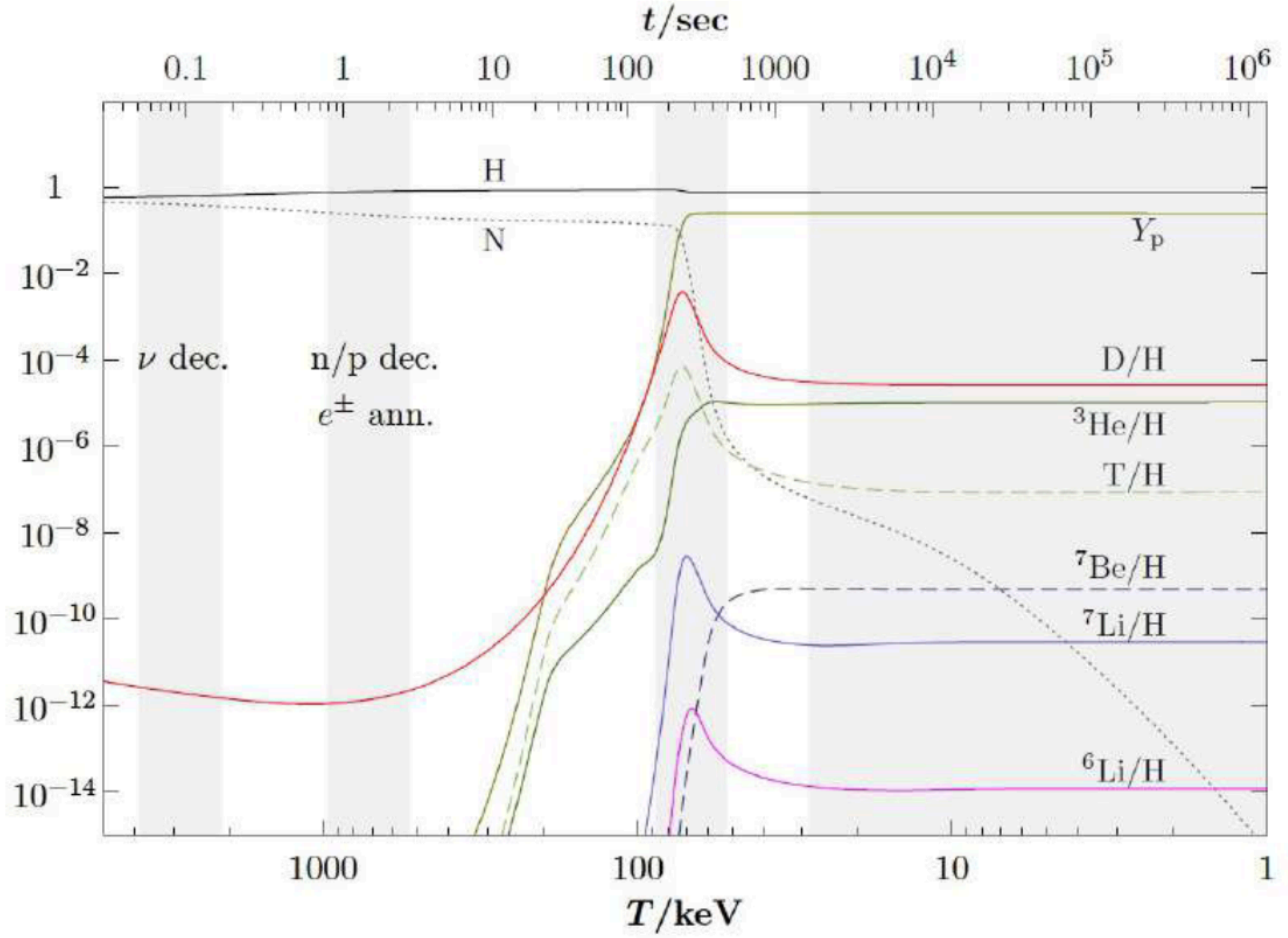
$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

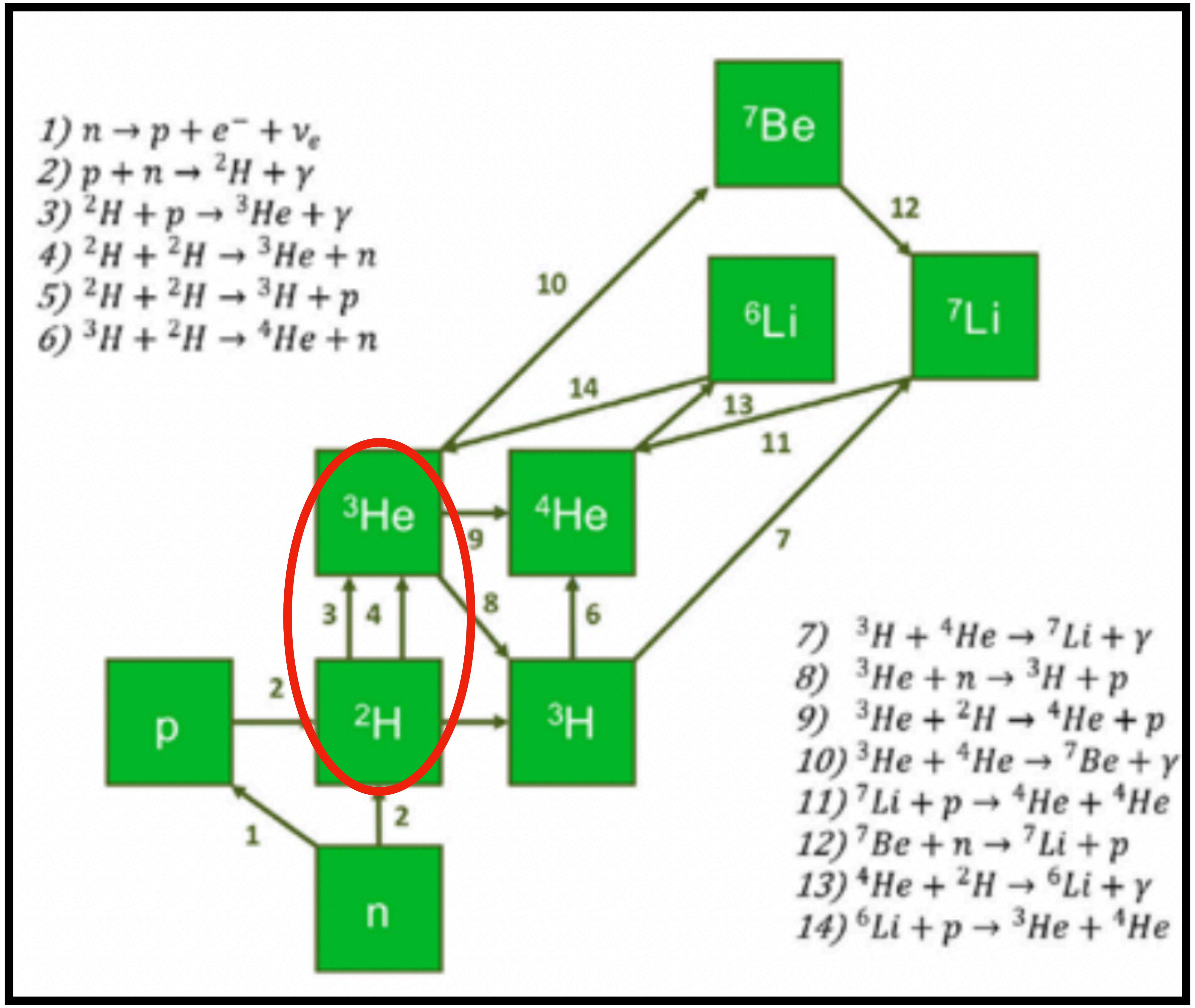
- **S(E) contains nuclear effects —> weak dependence on E**



Big Bang Nucleosynthesis

- 3 minutes after the Big Bang
- 3 chemical elements - H, He, Li
- 3 observed abundances - ^2H, ^4He and ^7Li





Astrophysical Motivation: $^2H(p, \gamma)^3He$

- Primordial Deuterium Abundance (D/H) is highly sensitive to Baryon density.

- Using the cosmological parameters (PLANCK 2018) ,

$$\frac{N(^2H)}{N(H)} = (2.51 \pm 0.07)10^{-5} \longleftarrow \textbf{BBN Theory}$$

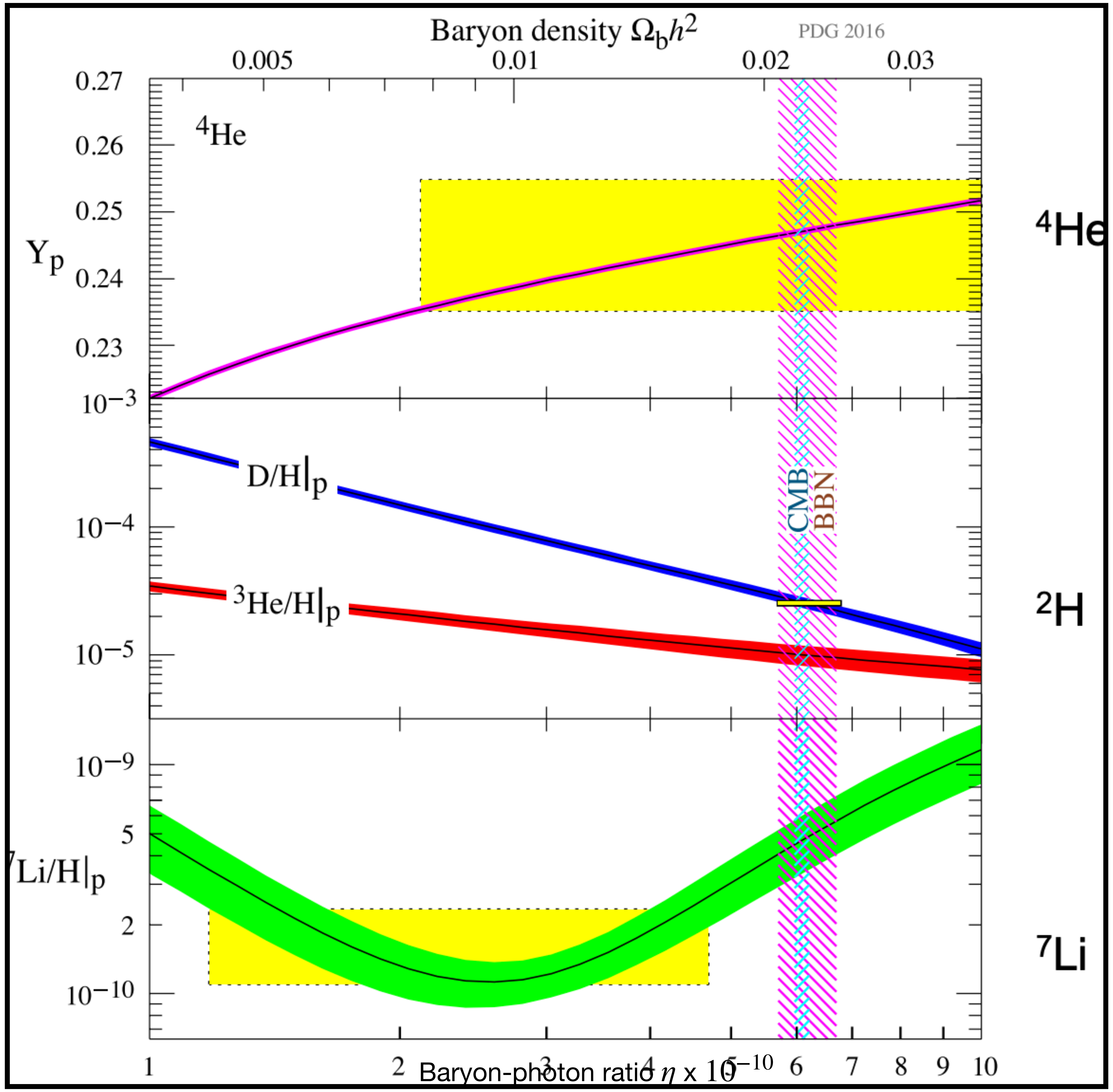
- Observations of primordial clouds -

$$\frac{N(^2H)}{N(H)} = (2.547 \pm 0.03)10^{-5} \longleftarrow \textbf{Observations}$$

Off by 0.5%

Incomplete knowledge of reaction cross-sections in BBN!

Proton Capture of D (Q = 5.493 MeV) —> dominant process for D destruction



State of the Art: $^{2}H(p, \gamma)^{3}He$

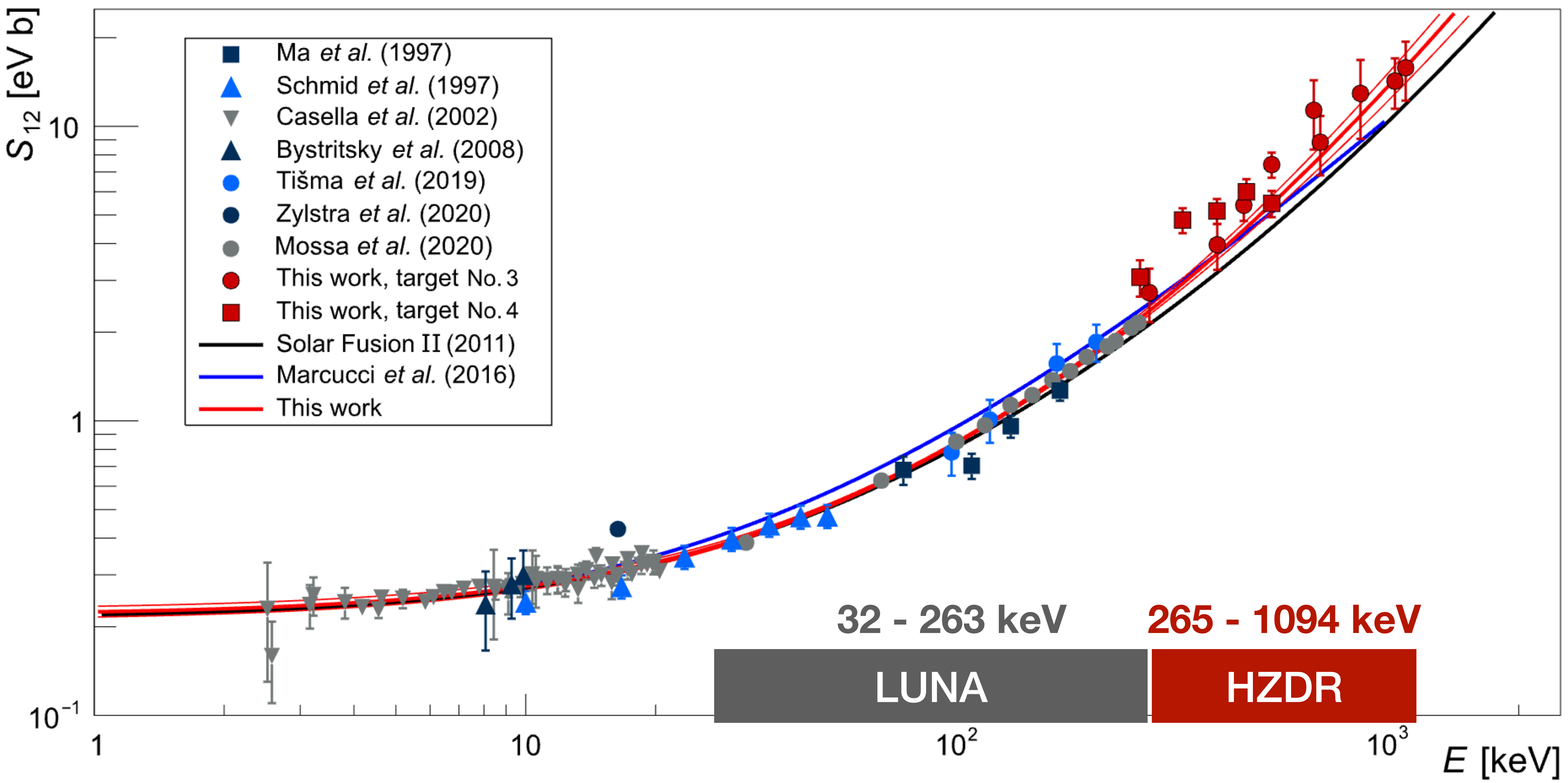
LUNA

- Energy: **32 - 263 keV**
- LUNA 400 kV accelerator
- Windowless gas target
- BGO and HPGe setup

HZDR

- **265 - 1094 keV**
- Solid target
- HPGe

Turkat et al. (2021)

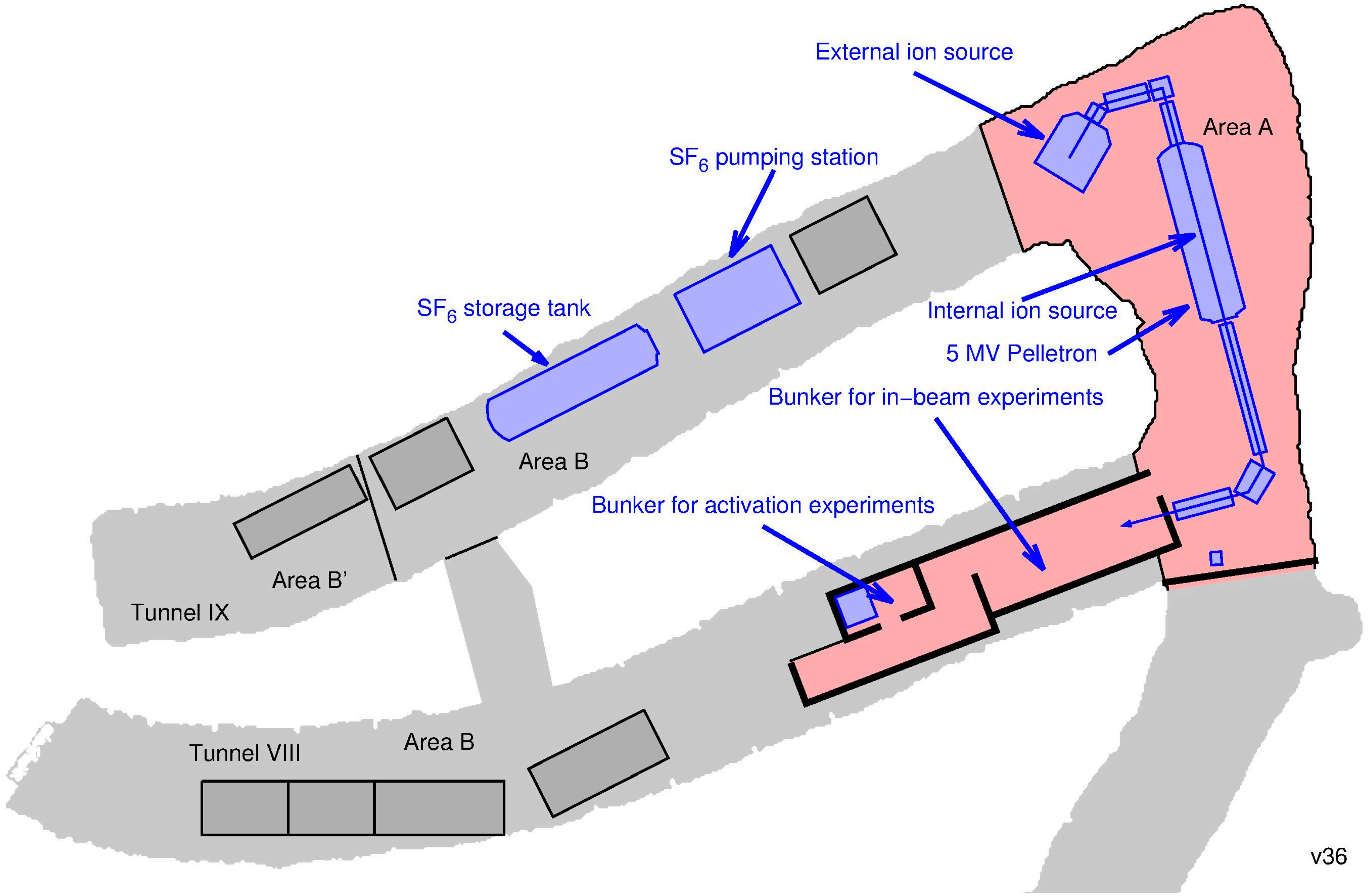


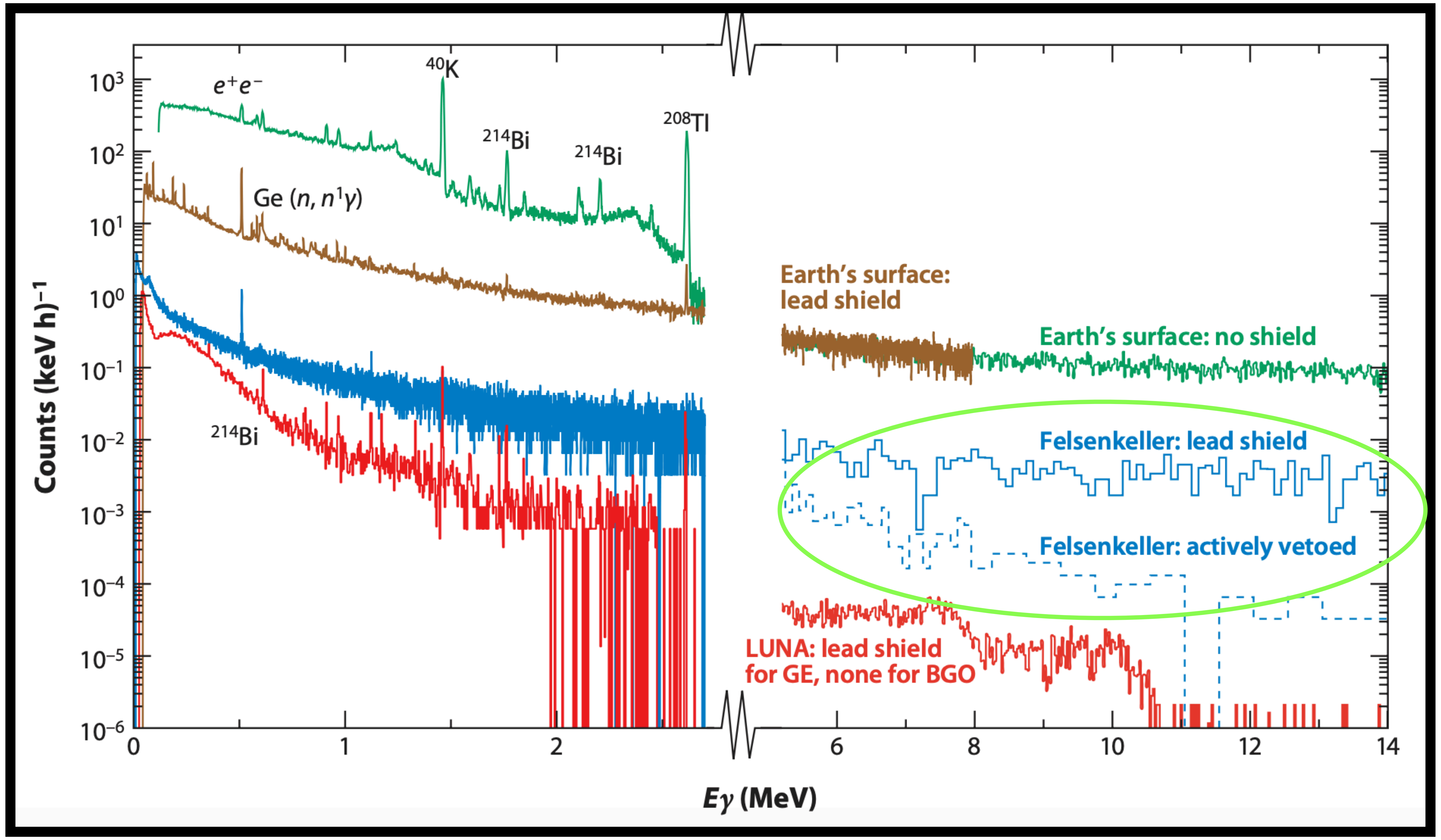
- **10% discrepancy between LUNA extrapolation and HZDR data!**
- **New measurement needed to confirm LUNA findings constrain the tension with high energy data.**

$^{2}H(p,\gamma)^{3}He$

Felsenkeller Accelerator

- 5 MV Pelletron accelerator, 30 μA proton/ molecular beam in single-ended and tandem mode.
- 45 m rock overburden — 99% muon and neutron suppression



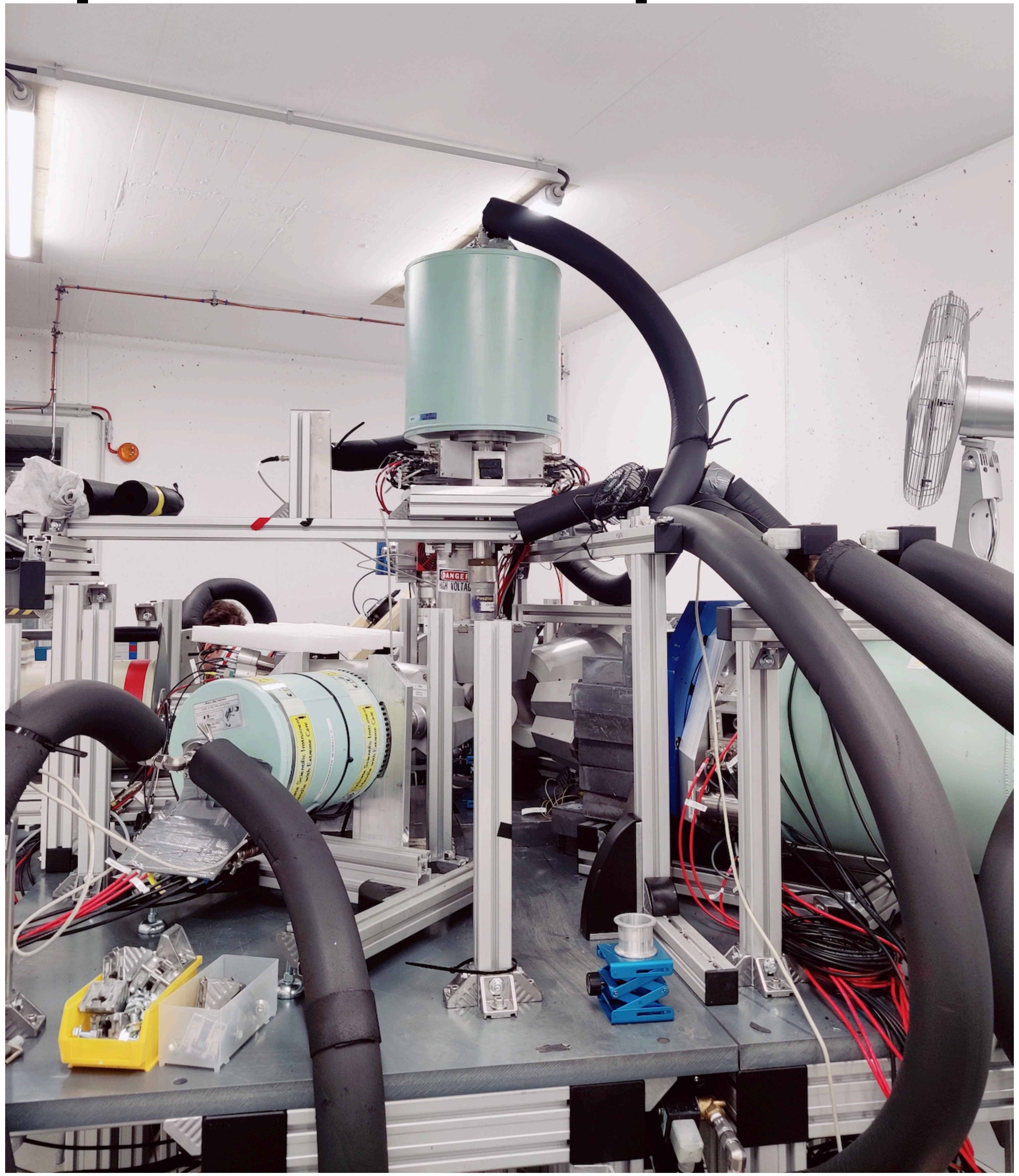


Natural Radioactivity < 3.0 MeV

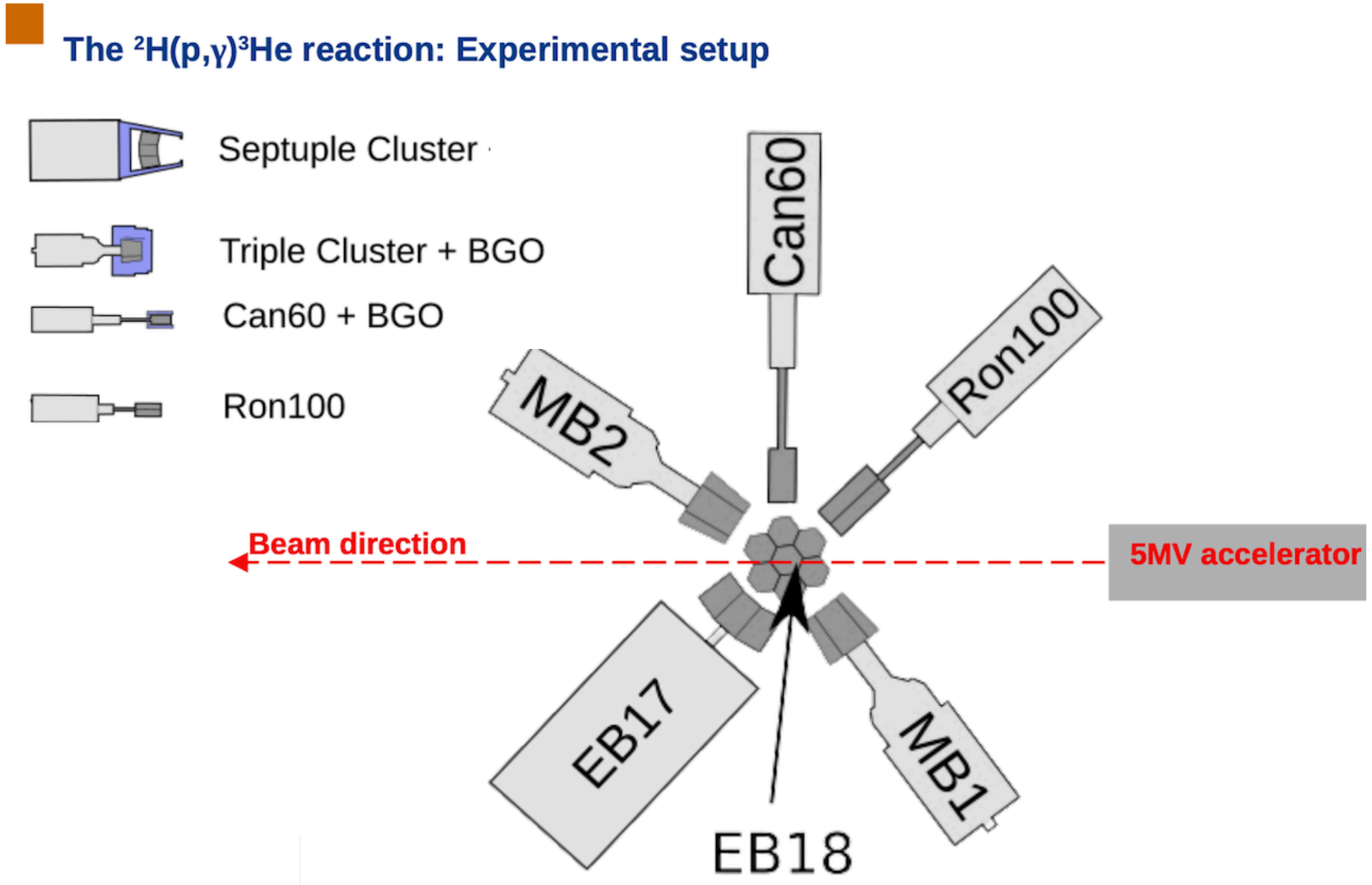
Cosmic Muons and neutrons > 3.0 MeV

$^{2}H(p,\gamma)^{3}He$

Experimental Setup



- Energy: **300 - 800 keV**
- Intensity: **5 μA** beam of $^{1}H^{+}$ beam
- Target: 2 types of solid deuterated targets
  - TiD (HZDR)
  - ZrD_2 (INFN, Legnaro)
- Detector: 6 HPGe detectors



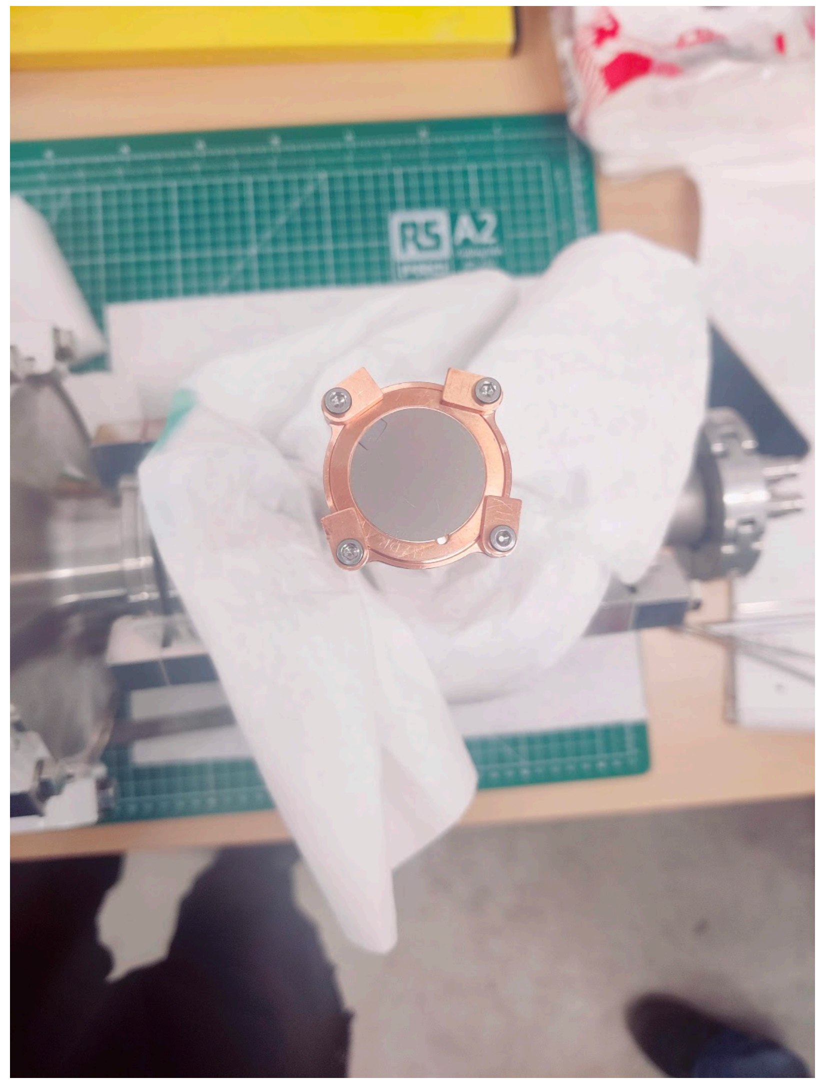
$^2H(p, \gamma)^3He$: Efficiency

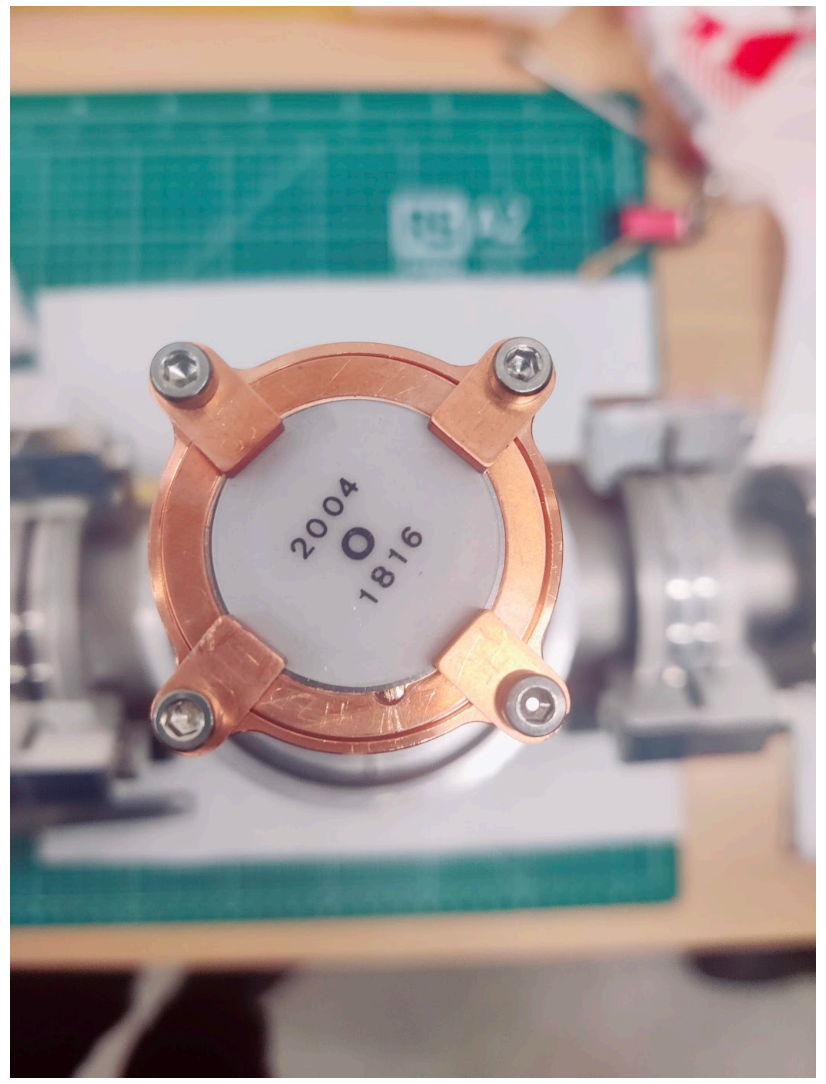
Detector Calibration

- ^{60}Co, ^{137}Cs, ^{88}Y and ^{22}Na —> covers from 662 keV to 1836 keV
- $^{27}Al(p, \gamma)^{28}Si$ (resonance at 992 keV) peaks extend calibration to high energies

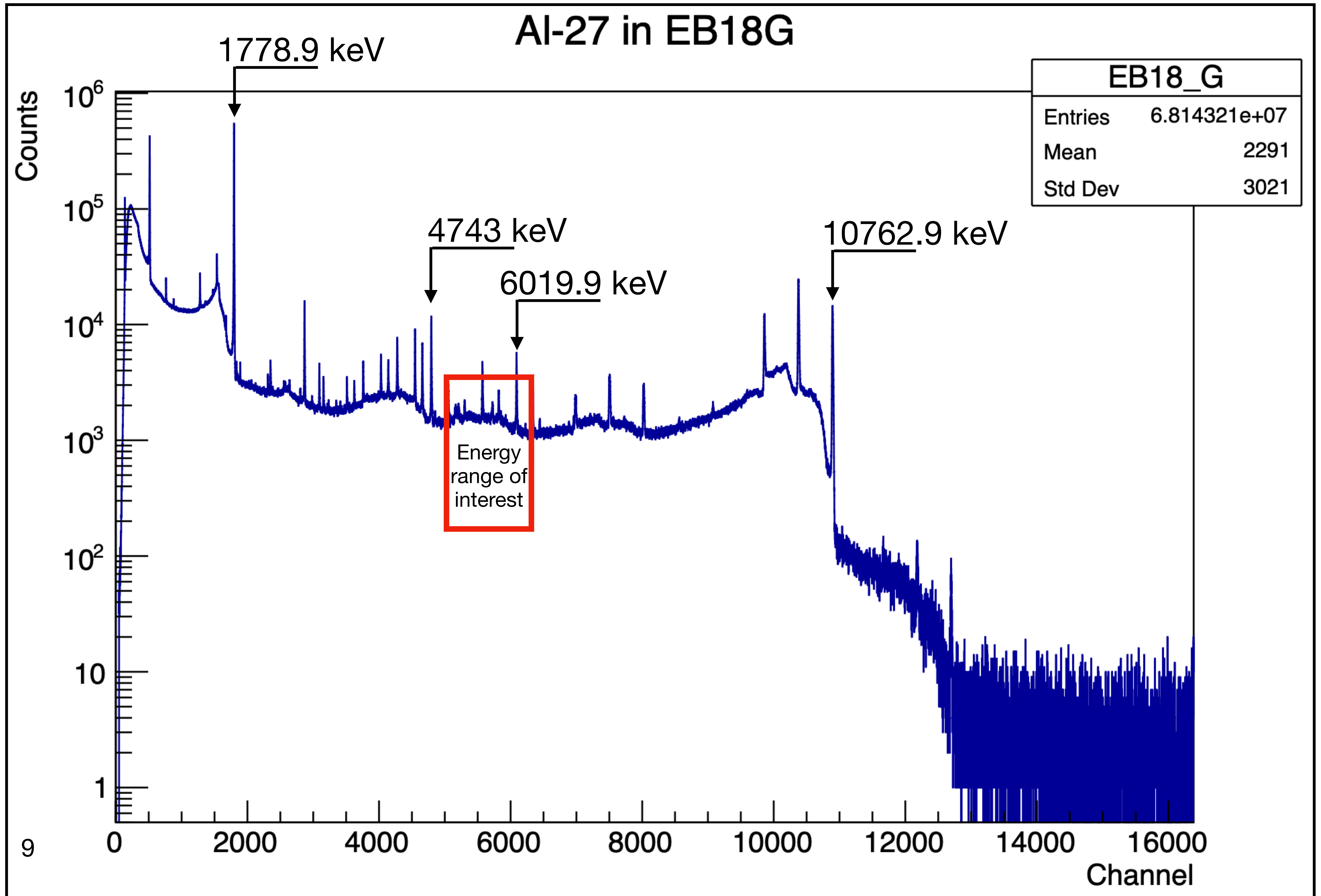
Source	γ-peak(s) (keV)
^{60}Co	1173.2, 1332.5
^{137}Cs	661.66
^{88}Y	898.04, 1836.06
^{22}Na	1274.5

^{137}Cs

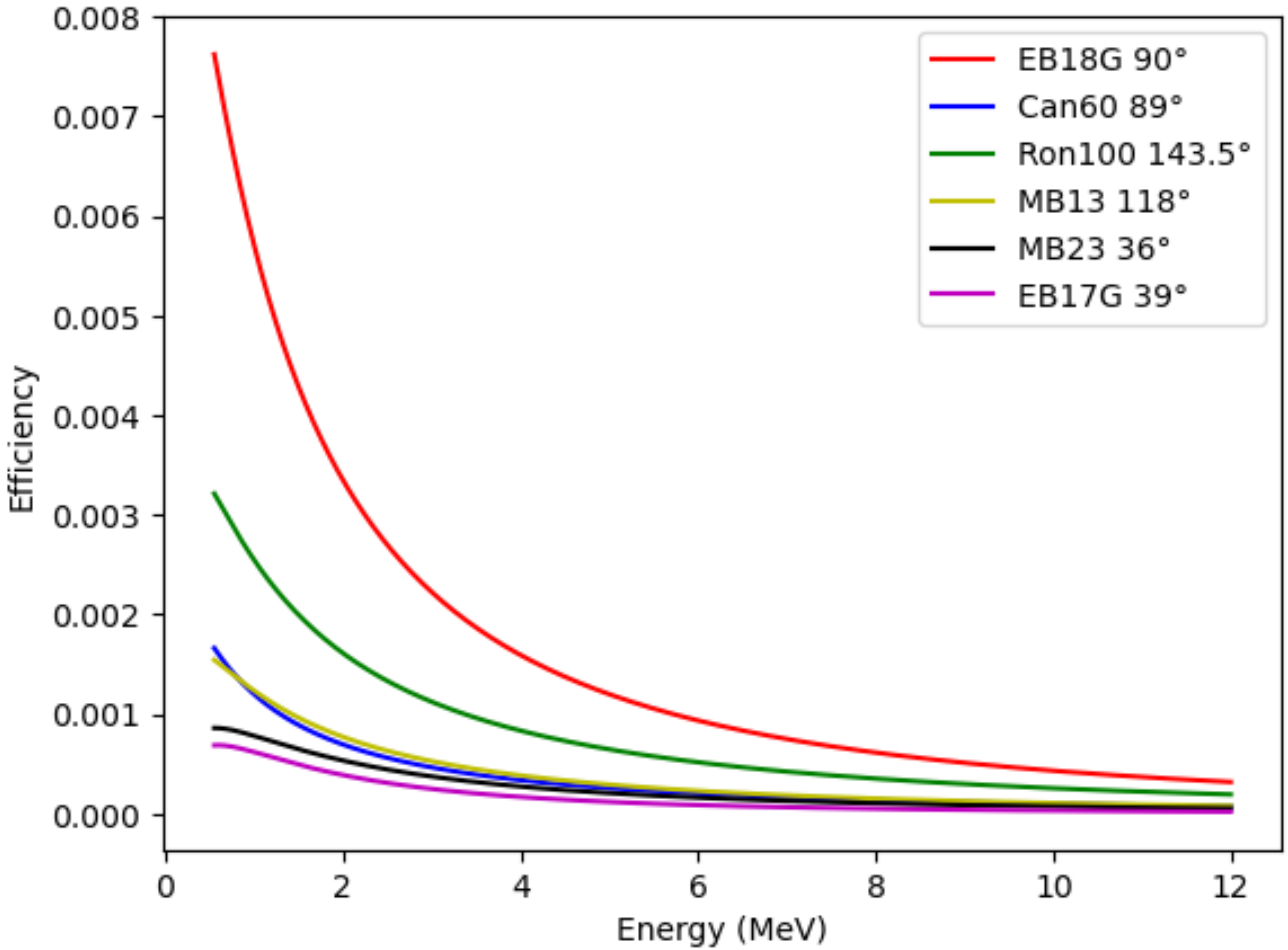




^{60}Co



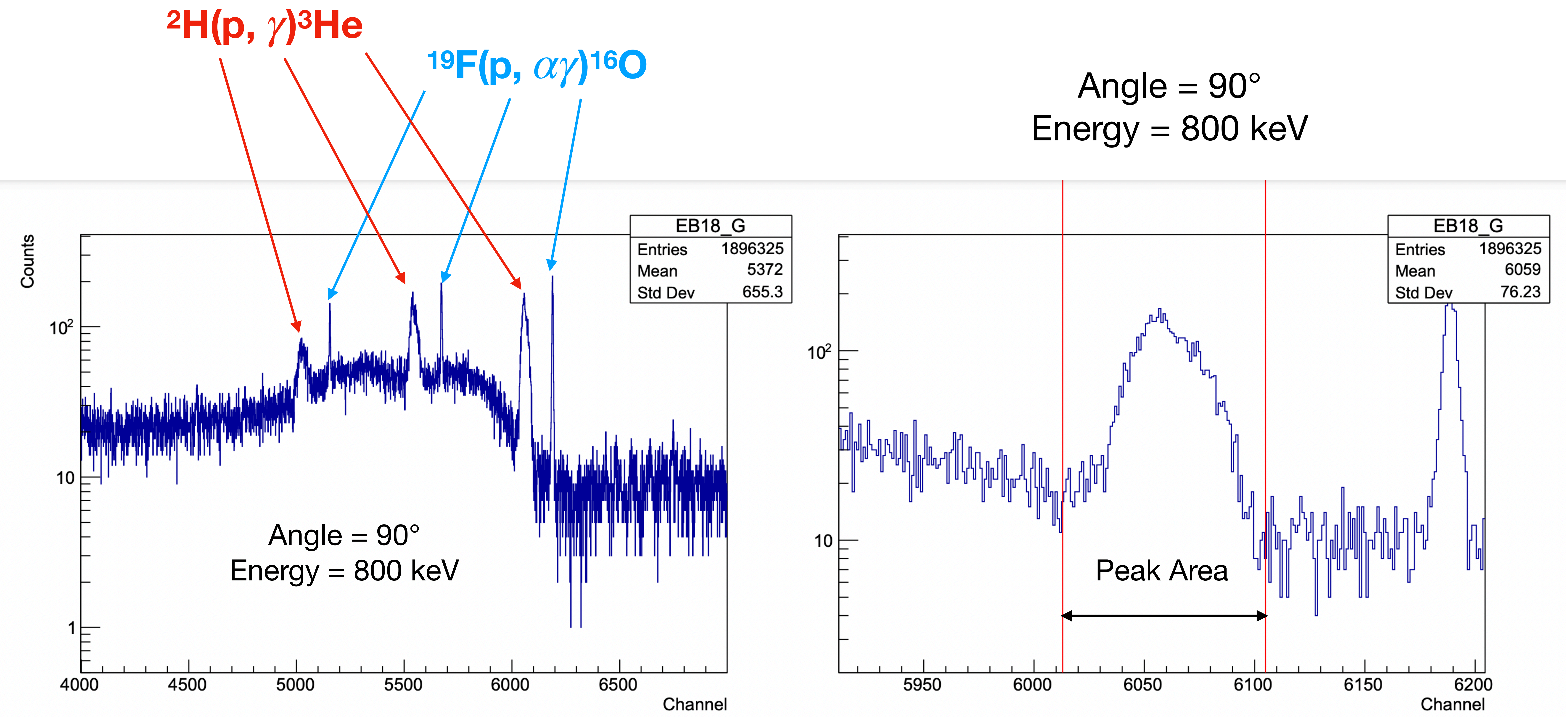
$^{2}H(p, \gamma)^{3}He$: Efficiency Results



$^{2}H(p, \gamma)^{3}He$: Spectra Analysis

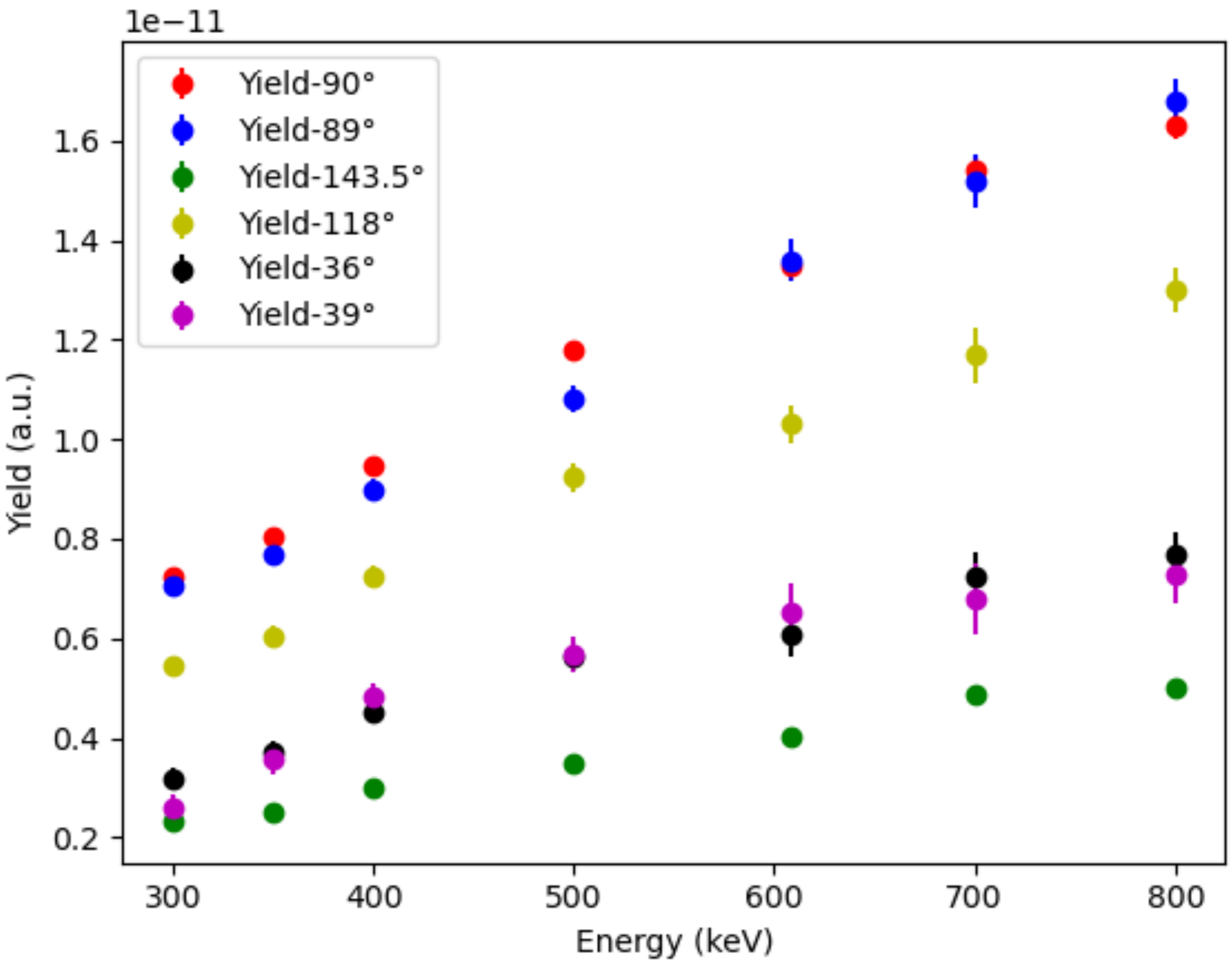
- ZrD_2 target irradiated from 300 to 800 keV.
- 608 keV reference run, repeated before each energy scan
- Beam induced background by ^{19}F
- Doppler and recoil corrections are applied

$$E_\gamma = Q + \frac{m_D}{m_{He}} E_p + \Delta E_{Dopp} - \Delta E_{Rec}$$



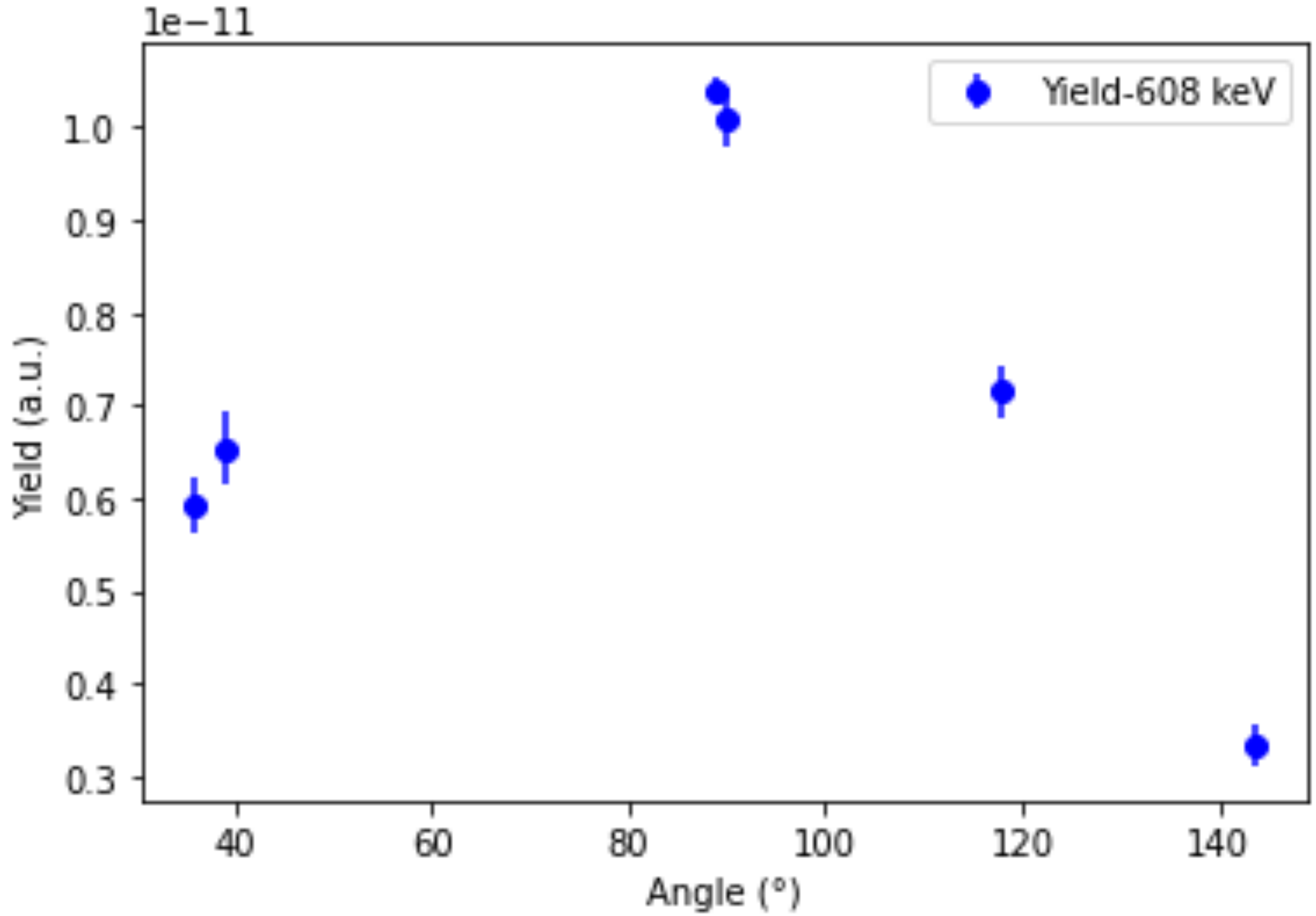
$^2H(p, \gamma)^3He$: Yield Results

- $Y = \frac{N_c}{\eta Q} . q$
- Good agreement b/w EB18G (90°) and Can60 (89°).
- Discrepancy due to angular distribution.



$^2H(p, \gamma)^3He$: Angular Distribution

EB18G ($90°$) - Yield v Angle at 608 keV



- $\frac{d\sigma}{d\Omega_{cm}}$ varies with $cos(\theta_{cm})$ and Energy

Angular Correction,

$$W(\theta) = 1 + \frac{1}{a_0} \sum a_l P_l(\theta)$$

- a_0, a_l from Marcucci et al. (ab-initio theory).

- $Y_{corr}(E) = \frac{Y(E, \theta)}{W(\theta)}$ -> this yield is used for S Factor calculation

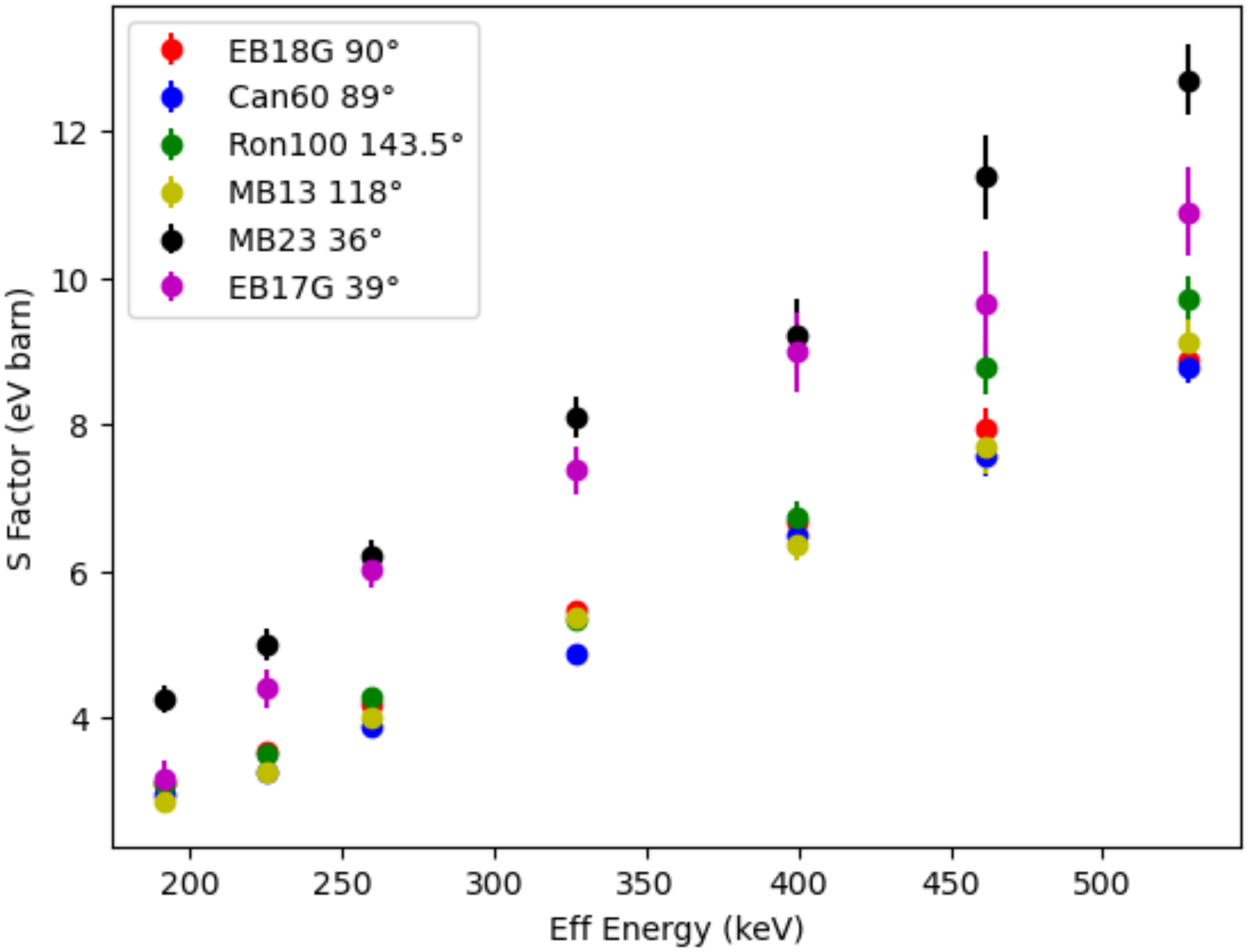
$^{2}H(p, \gamma)^{3}He$: Preliminary S-Factor

$$Y_{corr} = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\epsilon_{eff}(E)} dE$$

$$\boxed{S(E) = \frac{Y_{corr}}{\int_{E_0-\Delta E}^{E_0} \frac{e^{-2\pi\eta}}{E\epsilon_{eff}(E)} dE}}$$

$\epsilon_{eff}(E)$ is Effective Stopping Power. Depends on stoichiometry

- ΔE is the target thickness.
- Preliminary S Factor uncertainty of 3 to 5% (8% for EB17G).

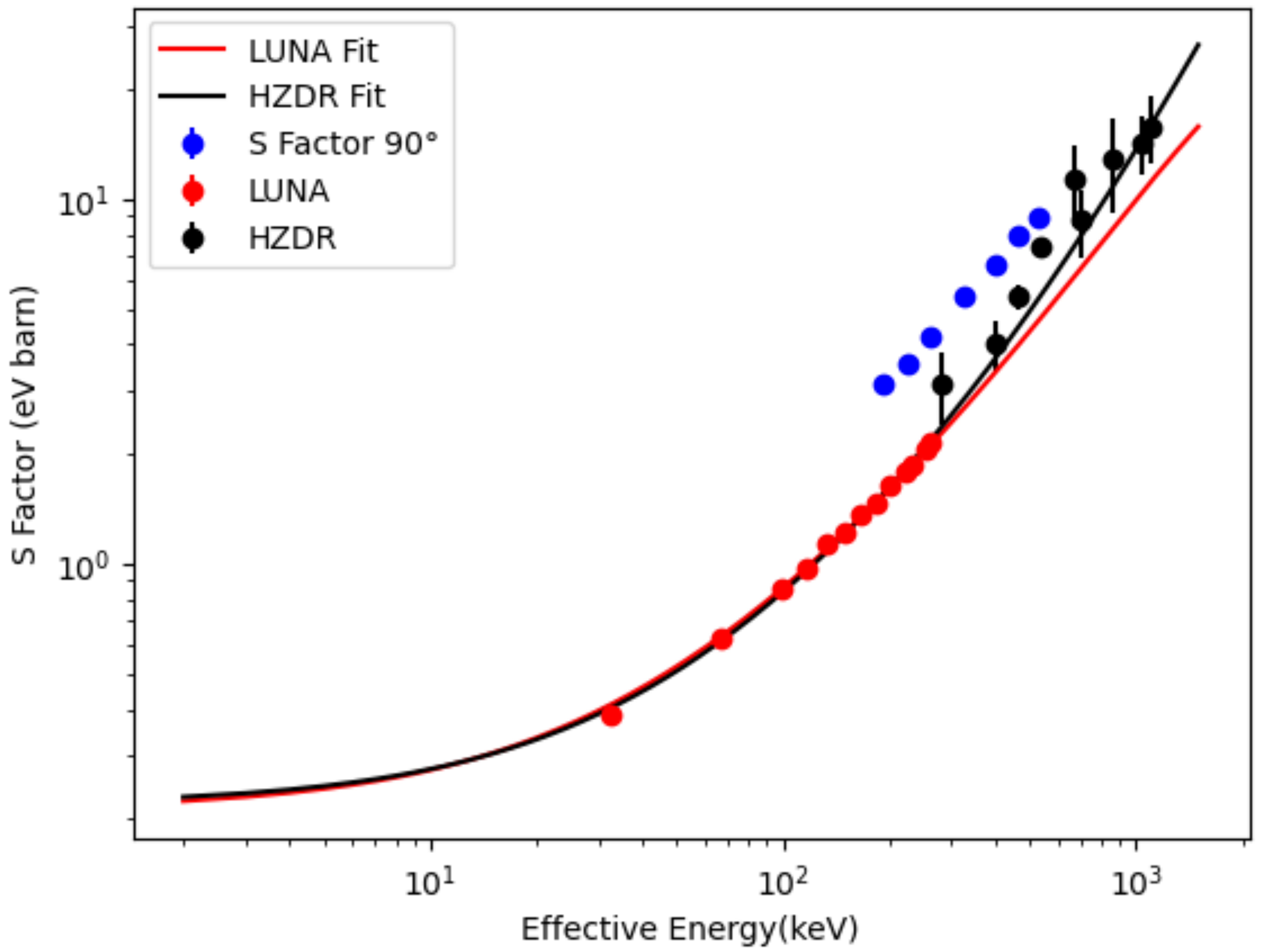


$^{2}H(p, \gamma)^{3}He$: Comparison to LUNA and HZDR

- Discrepancy with LUNA by a factor of 1.8. Possible mis-calibration of targets.
- Less scattered than HZDR

- Analysis of other targets underway.
- Additional target analysis ongoing —> reduce discrepancy.

EB18G ($90°$)- S Factor v Energy (keV)

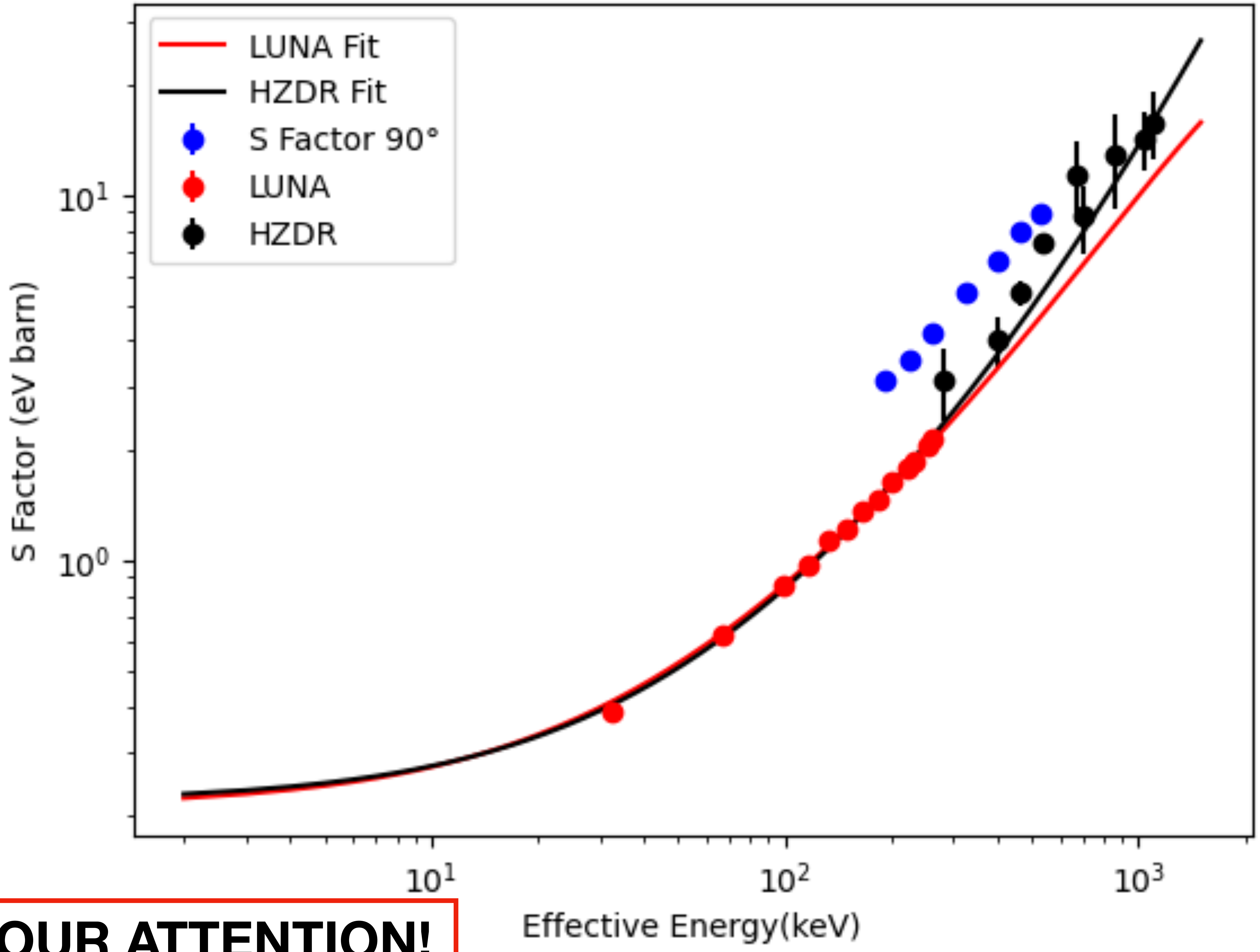


$^2H(p, \gamma)^3He$: Comparison to LUNA and HZDR

- Discrepancy with LUNA by a factor of 1.8. Possible mis-calibration of targets.
- Less scattered than HZDR

- Analysis of other targets underway.
- Additional target analysis ongoing —> reduce discrepancy.

EB18G (90°)- S Factor v Energy (keV)



THANK YOU FOR YOUR ATTENTION!

Experimental Challenges at Gamow Energy

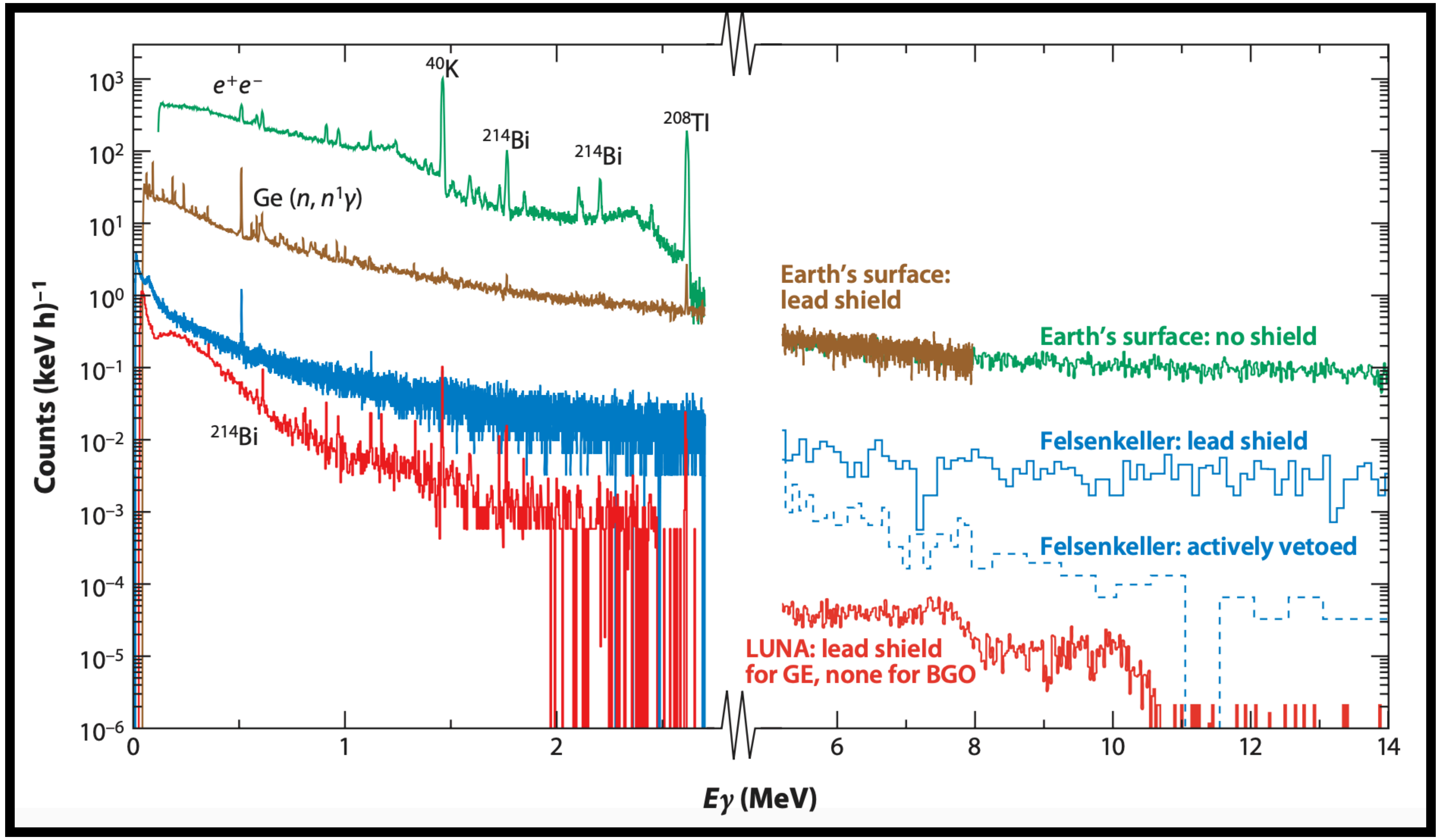
- $\sigma(E) \propto \frac{1}{E} e^{-b/\sqrt{(E)}}$ **—> drops exponentially at low E —> low count rate**
- **Background becomes significant —> affects our statistics!**

HOW DO WE OVERCOME THIS?

- **Underground Laboratories**

Eg: Felsenkeller: 99% reduction in muon and neutron flux

γ-ray background on Earth



$^{2}H(p, \gamma)^{3}He$: Data Analysis

Summing In/Out

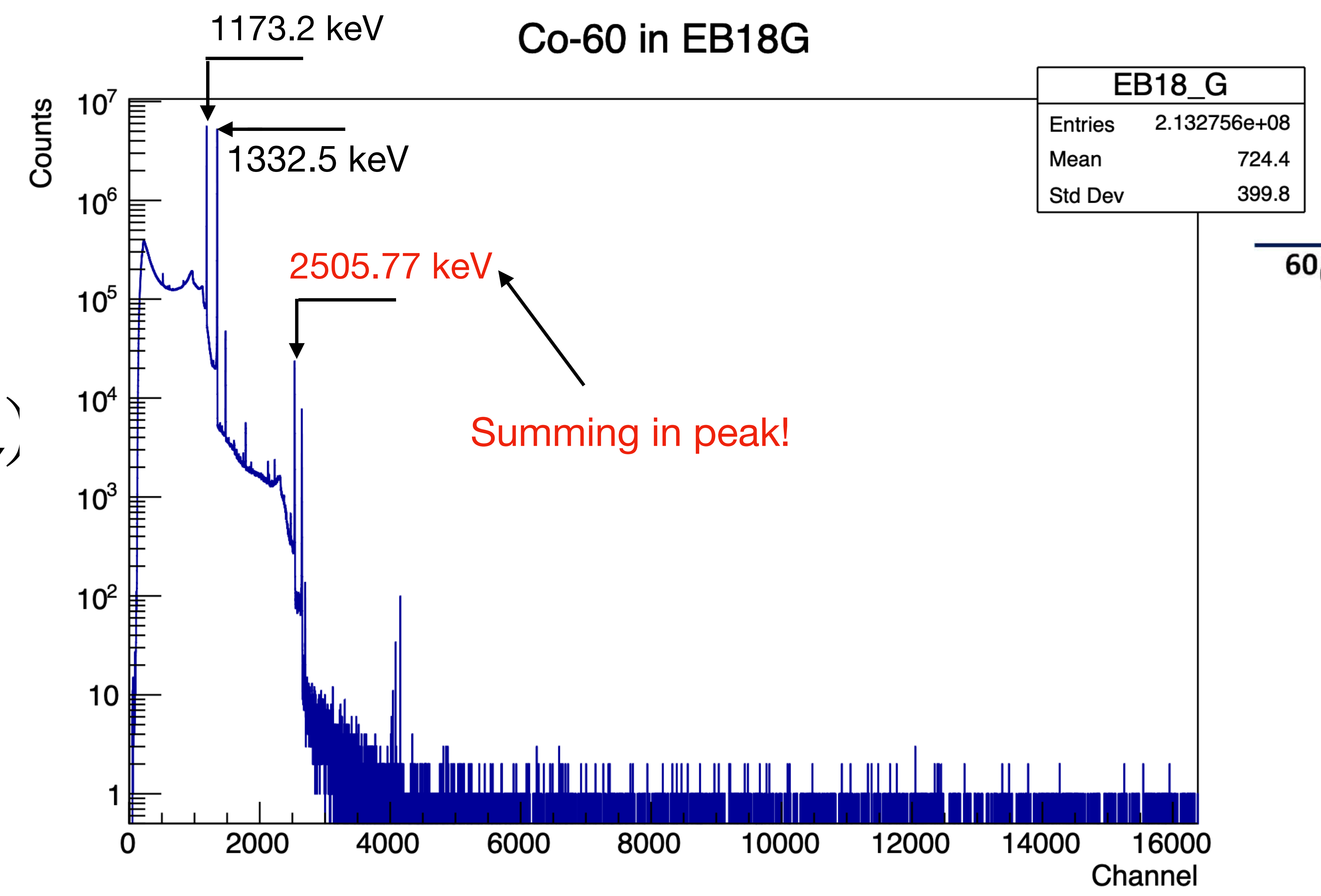
For ^{60}Co for example,

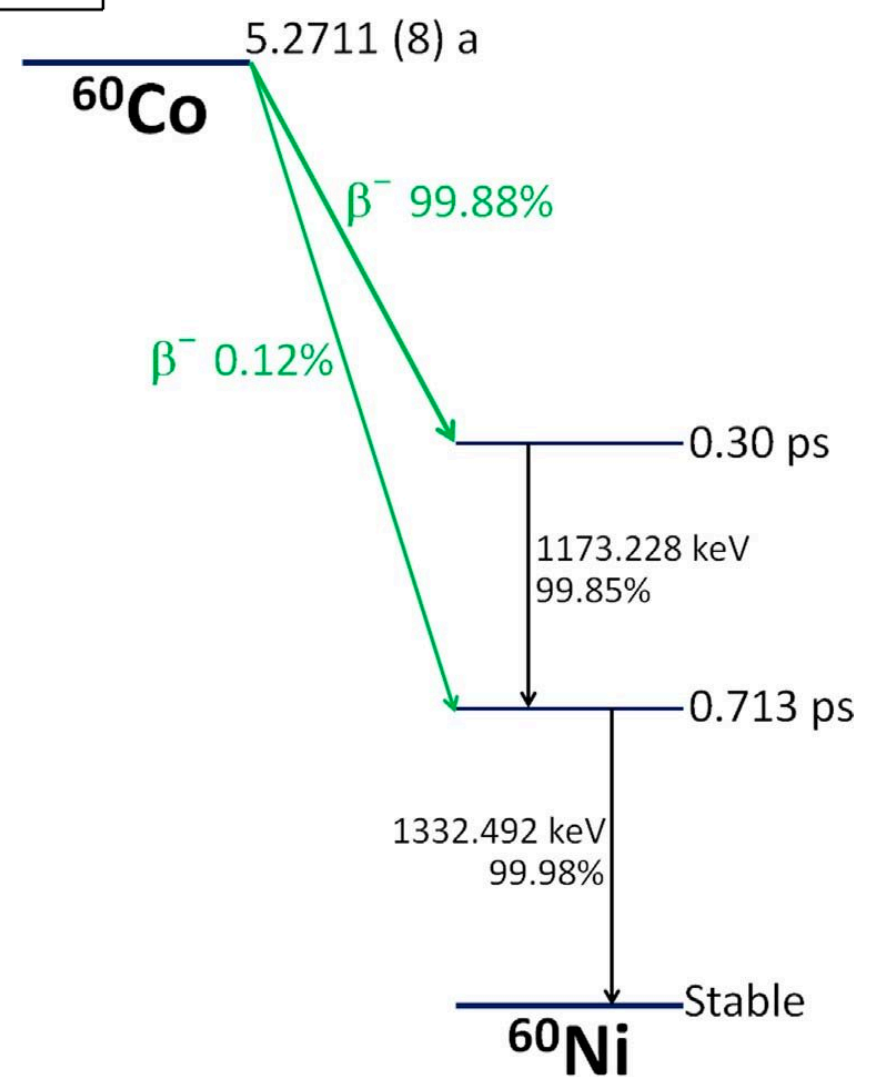
Detector Calibration

Multi-Parametric Approach

1. $\eta_{ph}(E_\gamma) = e^{a+bln(E_\gamma)+cln^2(E_\gamma)}$
2. $ln(\frac{\eta_{ph}}{\eta_{tot}}) = k_1 + k_2 ln(E_\gamma) + k_3 ln^2(E_\gamma)$

6 free parameters.





Steps

1. Observed Yield —> From spectra
2. Model Yield —> From equations
3. Minimise χ^2
4. Apply summing corrections

Summing Corrections

$$N(E_{\gamma 1}) = N_d b_1 \eta_{ph}(E_{\gamma 1})(1 - b_2 \eta_{tot}(E_{\gamma 2}))$$

$$N(E_{\gamma 2}) = N_d b_1 b_2 \eta_{ph}(E_{\gamma 2})(1 - \eta_{tot}(E_{\gamma 1}))$$

^{2}H(p, γ)^{3}He: Data Analysis

Step 3: S-Factor

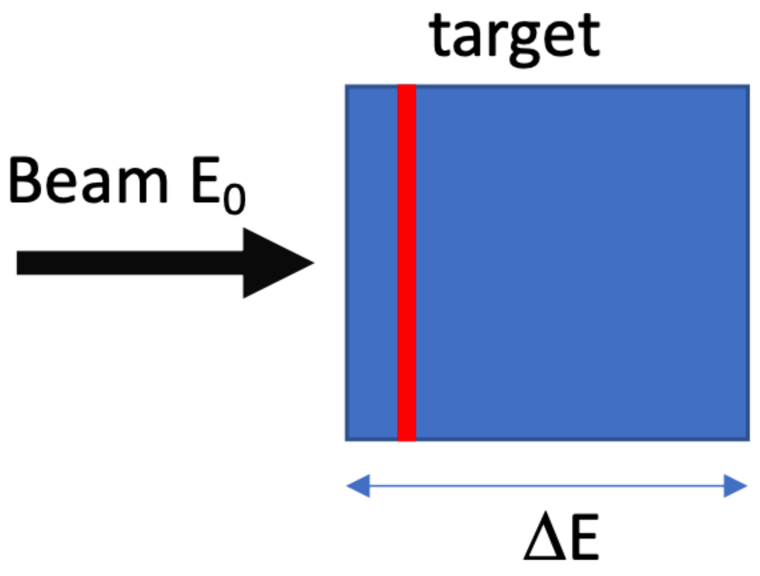
$$Y = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\epsilon_{eff}(E)} dE$$

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}$$

$$\boxed{S(E) = \frac{Y}{\int_{E_0-\Delta E}^{E_0} \frac{e^{-2\pi\eta}}{E\epsilon_{eff}(E)} dE}}$$

$\epsilon_{eff}(E)$ is Effective Stopping Power. Depends on stoichiometry

Y is converted to N_γ / N_p



ΔE is the loss of beam energy in the target

Beam energy is not constant!
We need E_{eff}