The study of the $^{7}Li(\gamma, t)\,^{4}He$ reaction with mono-energetic gamma-ray beams

Ioana KUNCSER
Gamma Driven Experiments Department, ELI-NP

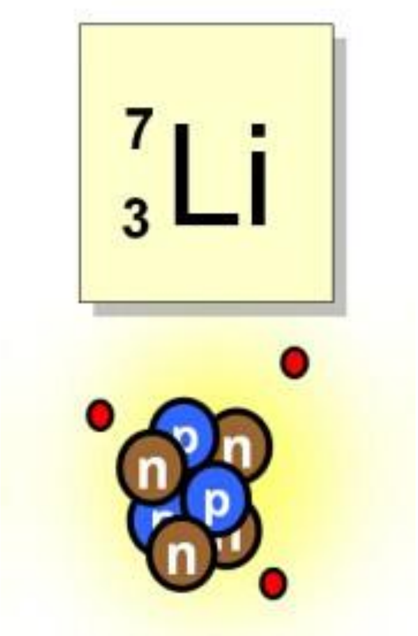
Young Researchers & Young Engineers Days - 2024

MOTIVATION OF THE EXPERIMENT

Big Bang Nucleosynthesis (BBN) → predicts the abundances of the light elements (produced in the early stages of the Universe)

“Cosmological Li problem”:

The measured ^{7}Li abundance is 3-4 times lower than expected ← Observations on the low-metallicity stars



- The stellar measurements are leading to anomalous results

OR

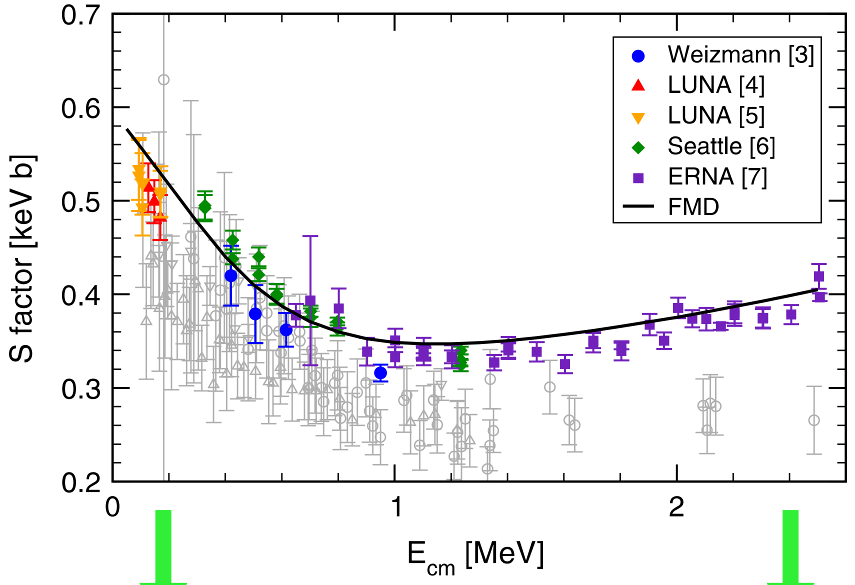
- An error is present in the nuclear theoretical models

The error can be related to the WMAP baryonic density

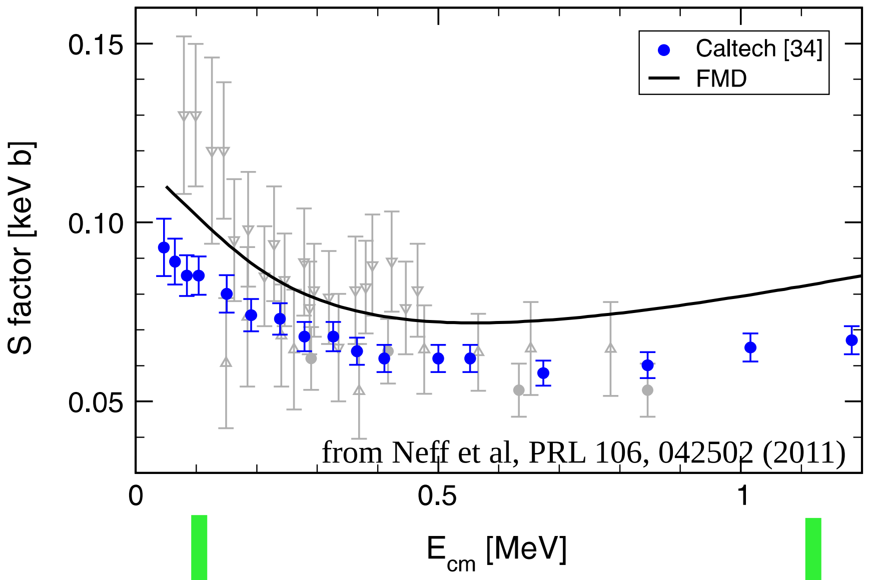
Lower value → higher effect of the $^{3}H(\alpha,\gamma)\,^{7}Li$ reaction.

Two main reactions are responsible for the production of mass 7 elements:

$^{3}He(\alpha,\gamma)\,^{7}Be$



$^{3}H(\alpha,\gamma)\,^{7}Li$



FMD (fully microscopic fermionic molecular dynamics approach) doesn't fit the experimental data for $^{3}H(\alpha,\gamma)\,^{7}Li$

→ $^{3}H(\alpha,\gamma)\,^{7}Li$: only a few experiments were performed

→ Due to restricted use & health/safety, an experiment with a tritium target cannot be performed anymore

However, the $^{3}H(\alpha,\gamma)\,^{7}Li$ reaction can still be studied by its INVERSE REACTION

Reciprocity Theorem:

Inverse reaction

$$\frac{\sigma_{Bb\to Aa}}{\sigma_{Aa\to Bb}} = \frac{(2j_A+1)(2j_a+1)k_{Aa}^2(1+\delta_{Bb})}{(2j_B+1)(2j_b+1)k_{Bb}^2(1+\delta_{Aa})} \Rightarrow \boldsymbol{\sigma_{Bb\to Aa} = k\cdot\sigma_{Aa\to Bb}}$$

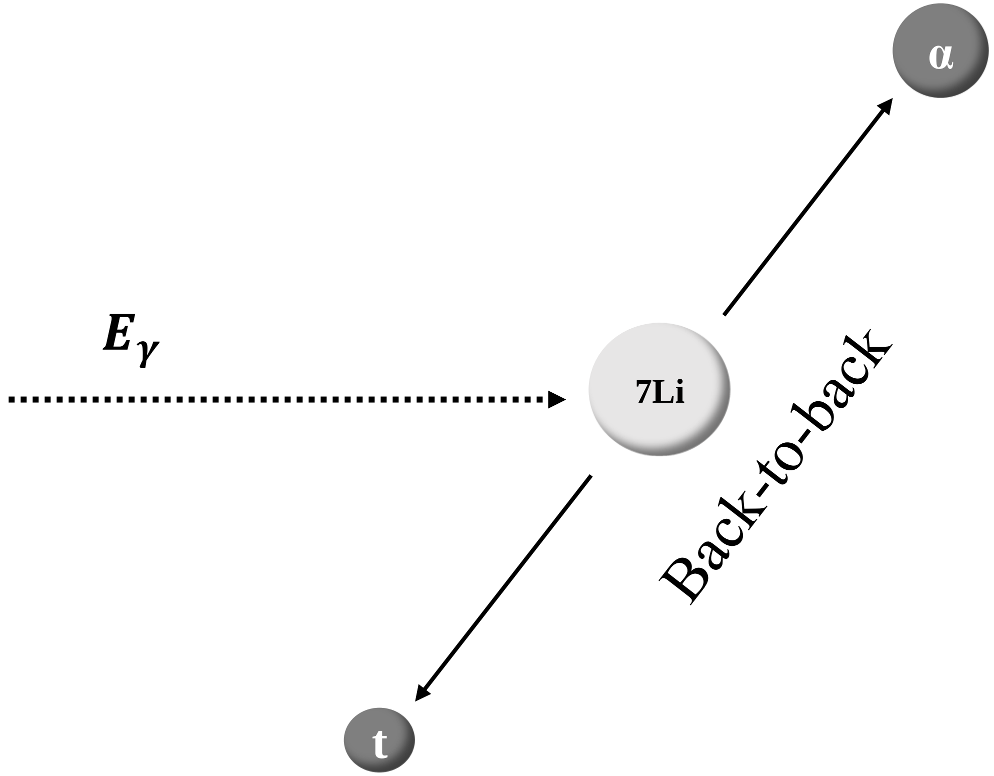
Direct reaction

*Photons: $2j_\gamma + 1 = 2$

$\boldsymbol{{}^3H(\alpha,\gamma)\,{}^7Li}$ → Direct reaction

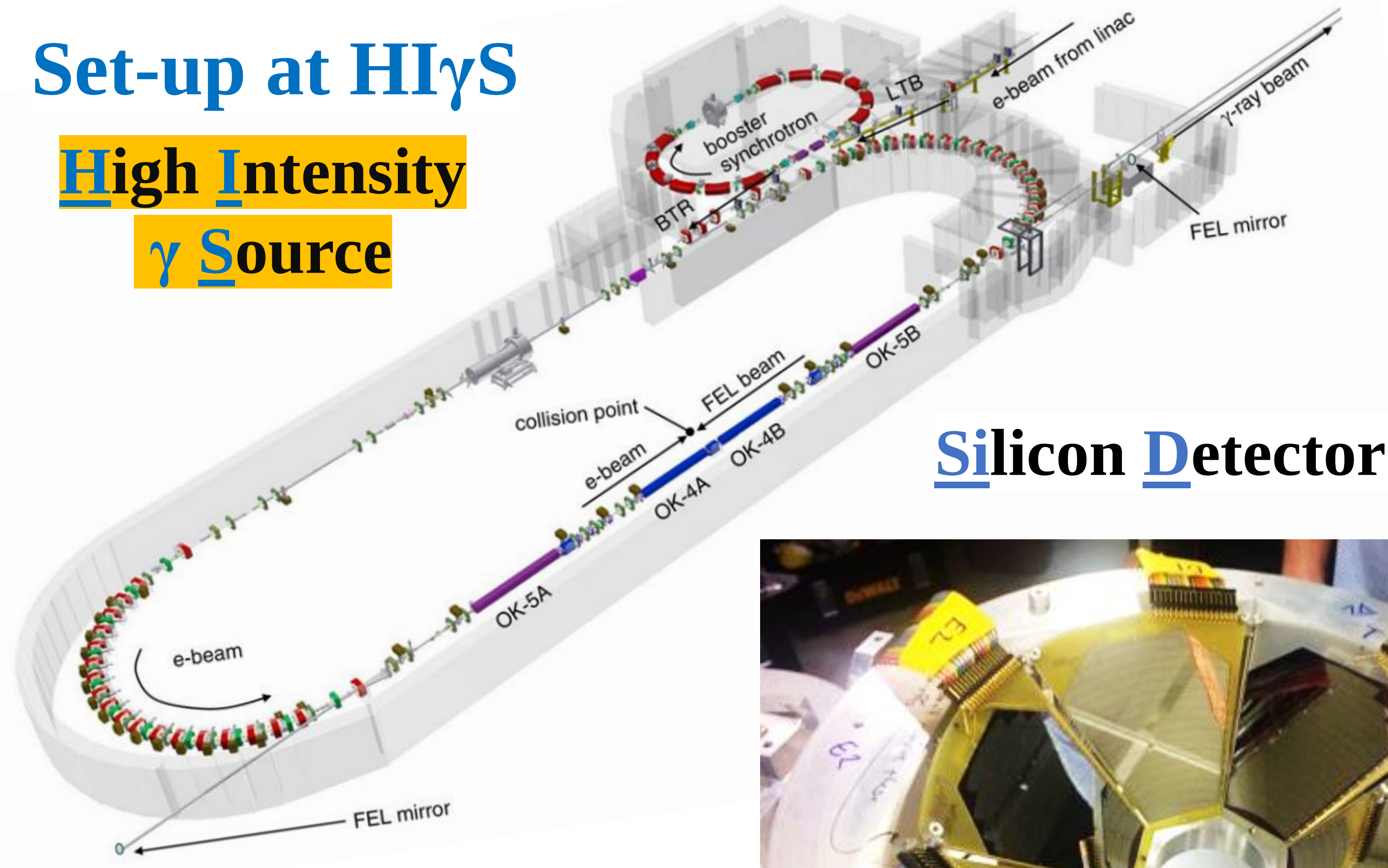
$\boldsymbol{{}^7Li(\gamma,t)\,{}^4He}$ → Inverse reaction

Lithium photodisintegration:
k ≈ 60



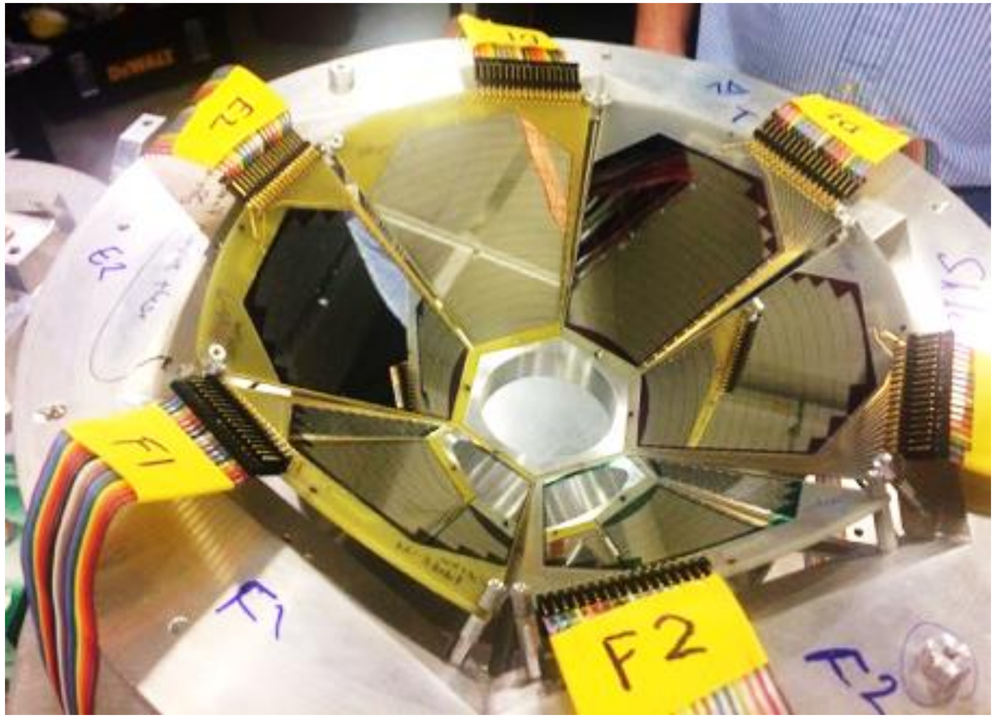
Set-up at HIγS

High Intensity γ Source



Energy:
1 MeV -100 MeV

Silicon Detector Array



LiF/Mylar

SIDAR

↓

Silicon
Detector
Array

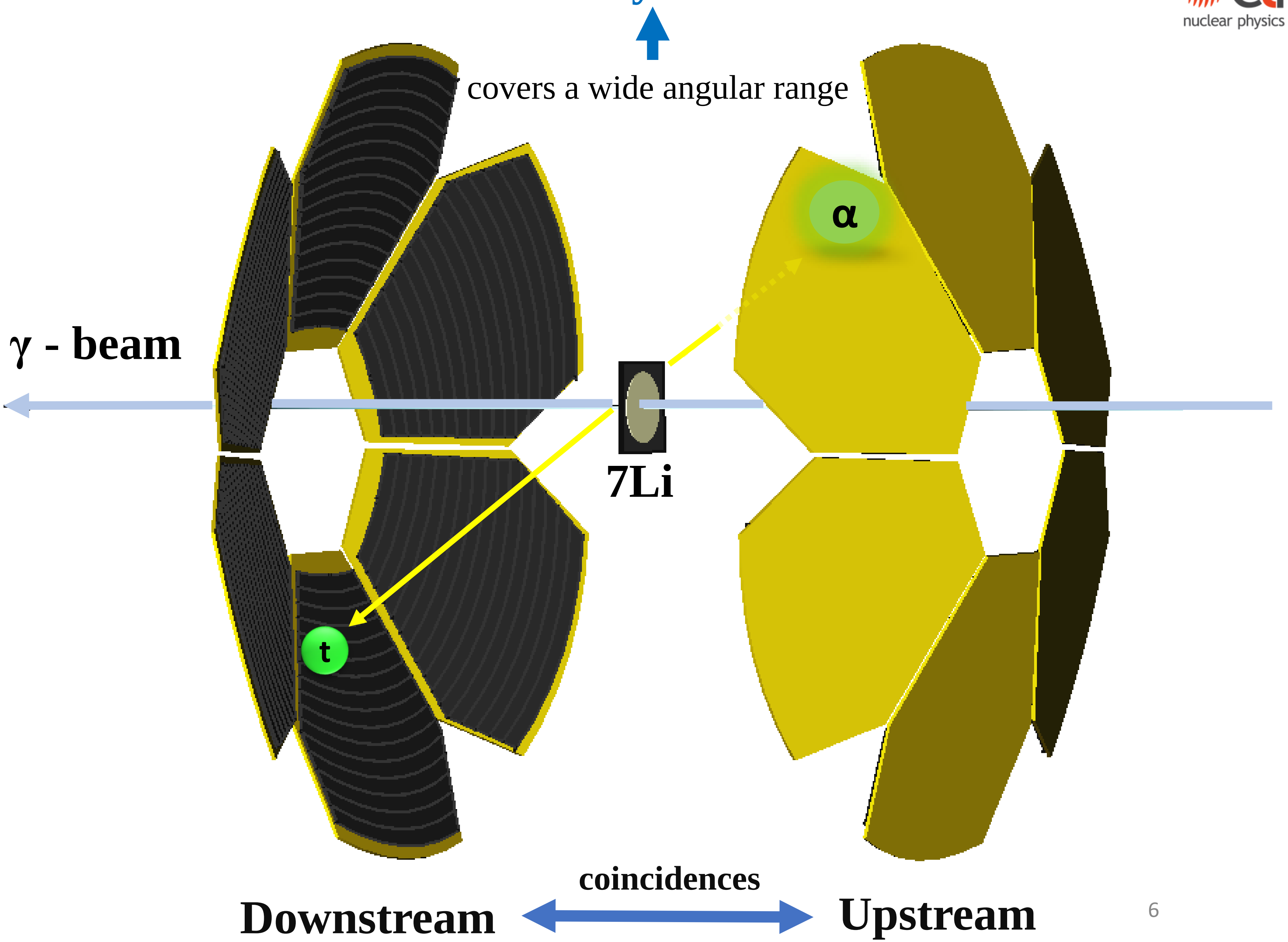
↓

2 x 6 YY1
(16 strips)

↓

192 channels

Efficiency ~ 38.66%



The old experiment:
2017
4.4 MeV - 10 MeV

energies above 6 MeV/thinner detectors

$\leftarrow {}^{7}Li(\gamma, t)^{4}He \rightarrow$

The new experiment:
6th April 2023-12th April 2023
3.7 MeV - 6 MeV

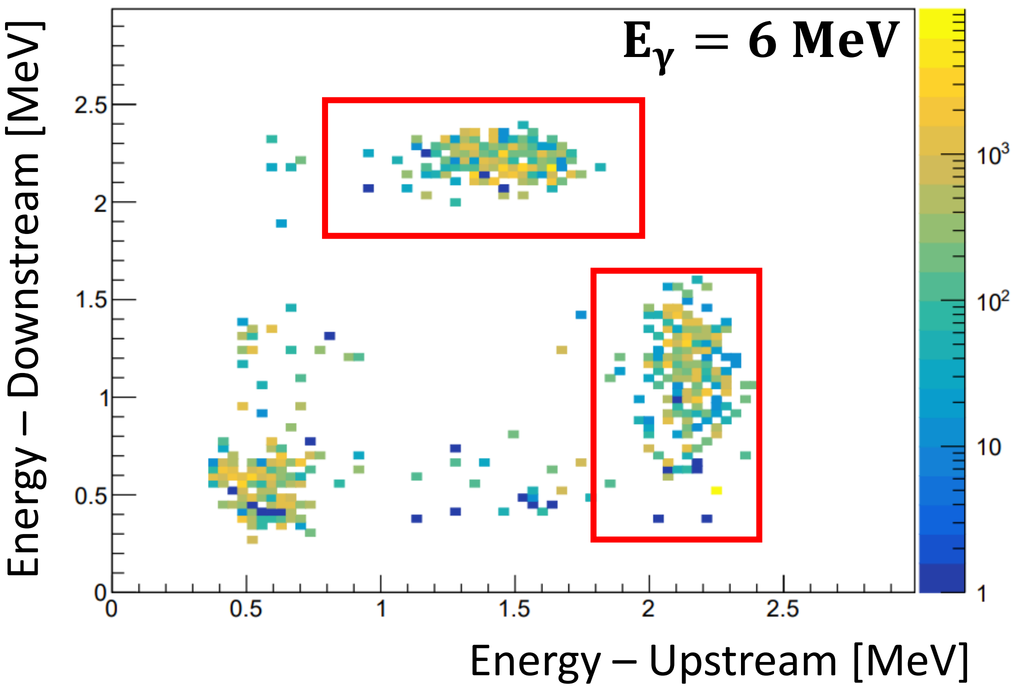
IMPROVEMENTS

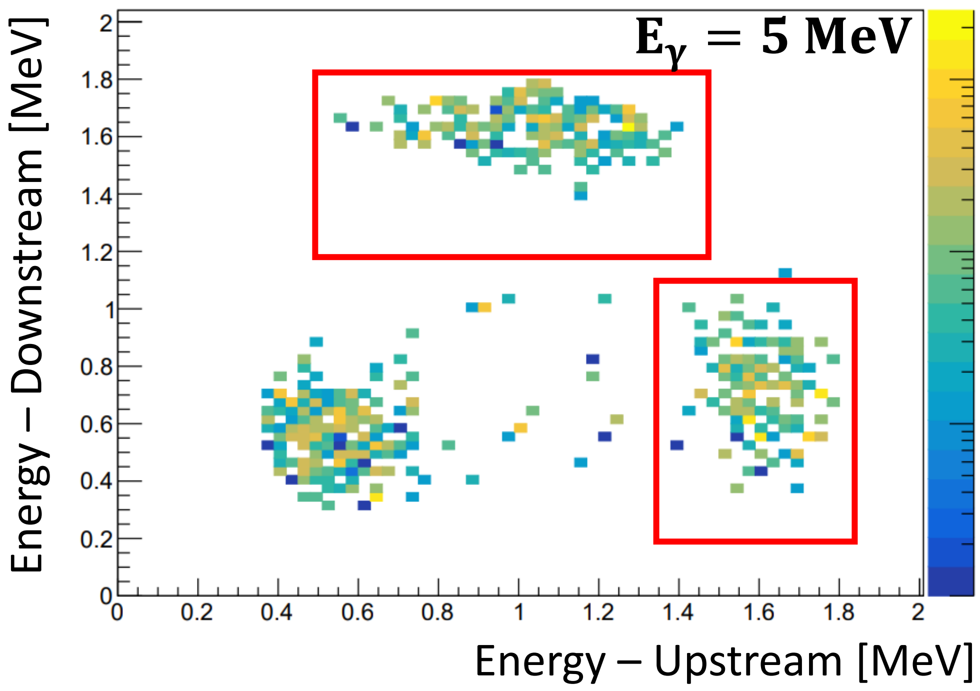
1. **ARRAY OF THINNER Si DETECTORS: 100&65μm**
2. **THINNER ENTRY FLANGE**
3. **REDUCED ELECTRON DENSITY IN THE FLANGE (Al instead of stainless steel)**
4. **LONGER VACUUM PIPE (in front of the chamber)**

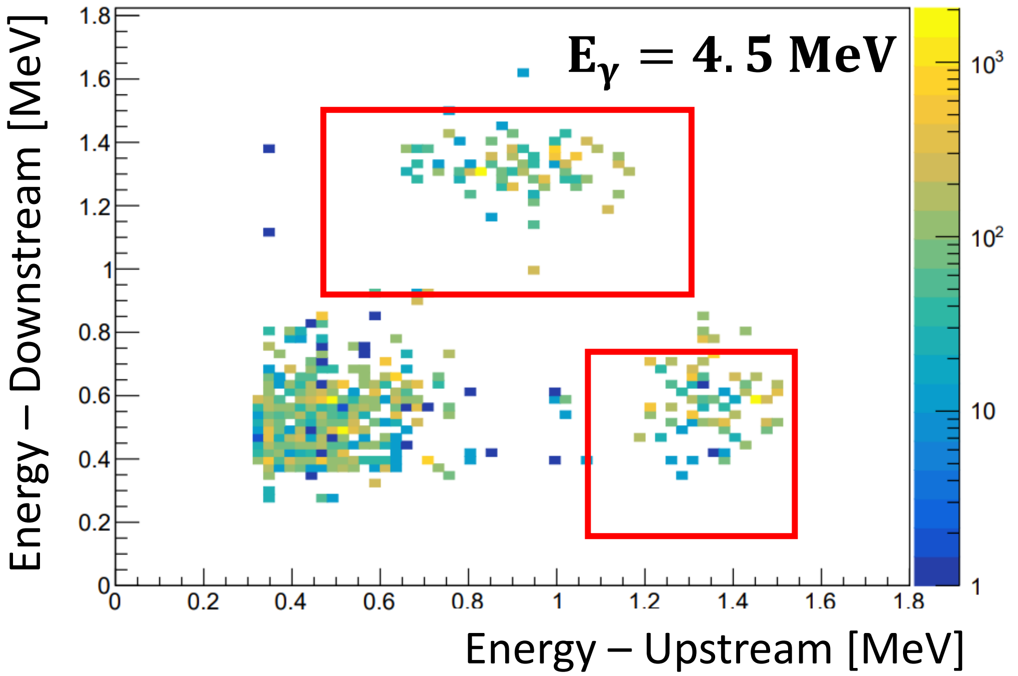
→ **The coincidences have been clearly separated even for the lowest energy**

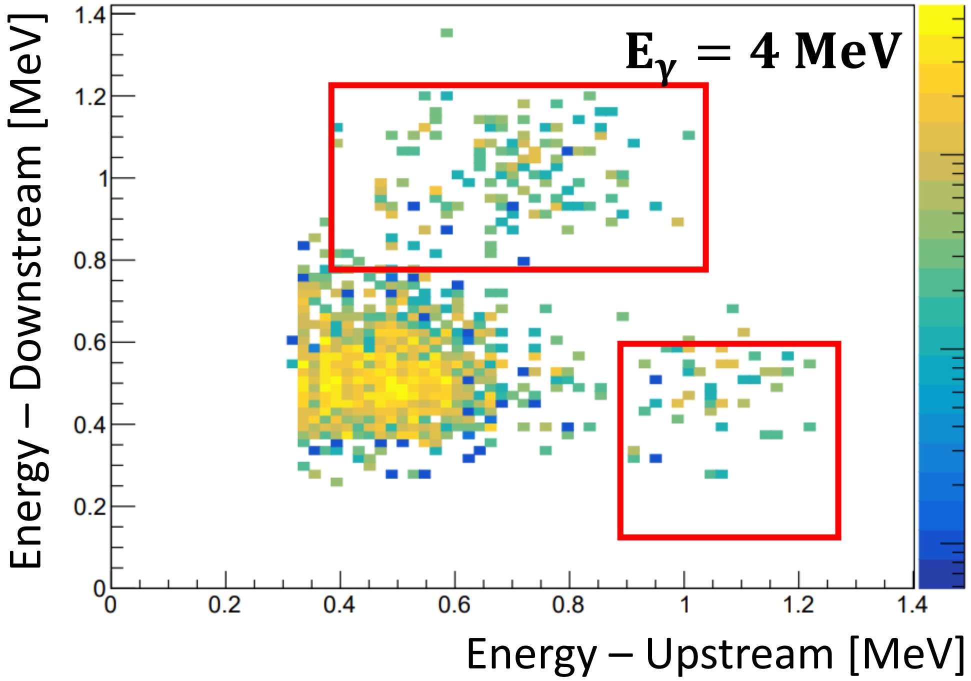
→ **The background has been highly reduced**

PRELIMINARY RESULTS









PRELIMINARY RESULTS

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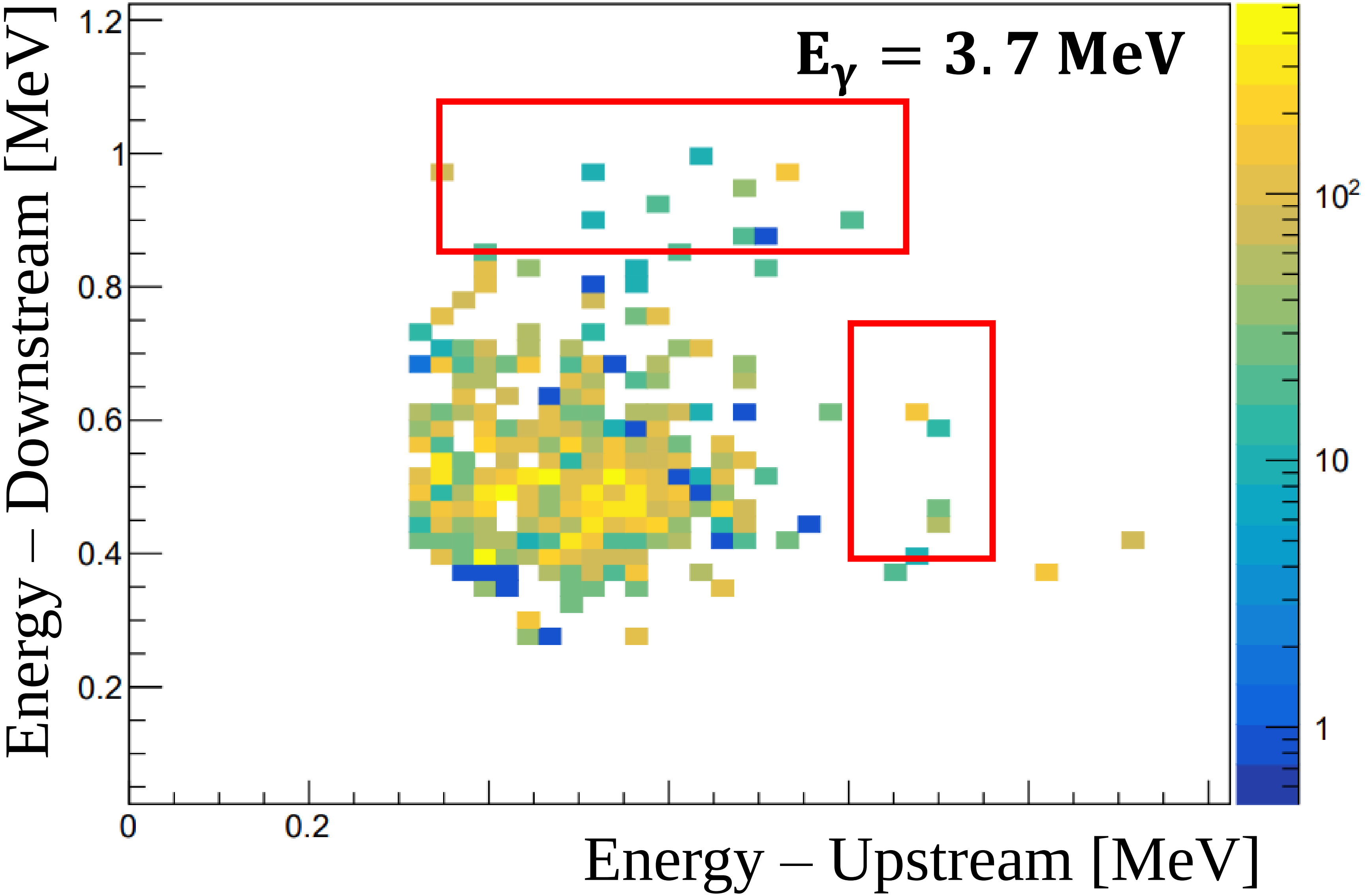


The ground state cross-section of the inverse $^{7}Li(\gamma,\alpha)\,^{3}He$ reaction

Number of coincidences

$$\sigma = \frac{R}{N_{beam} \cdot N_{target} \cdot \varepsilon}$$

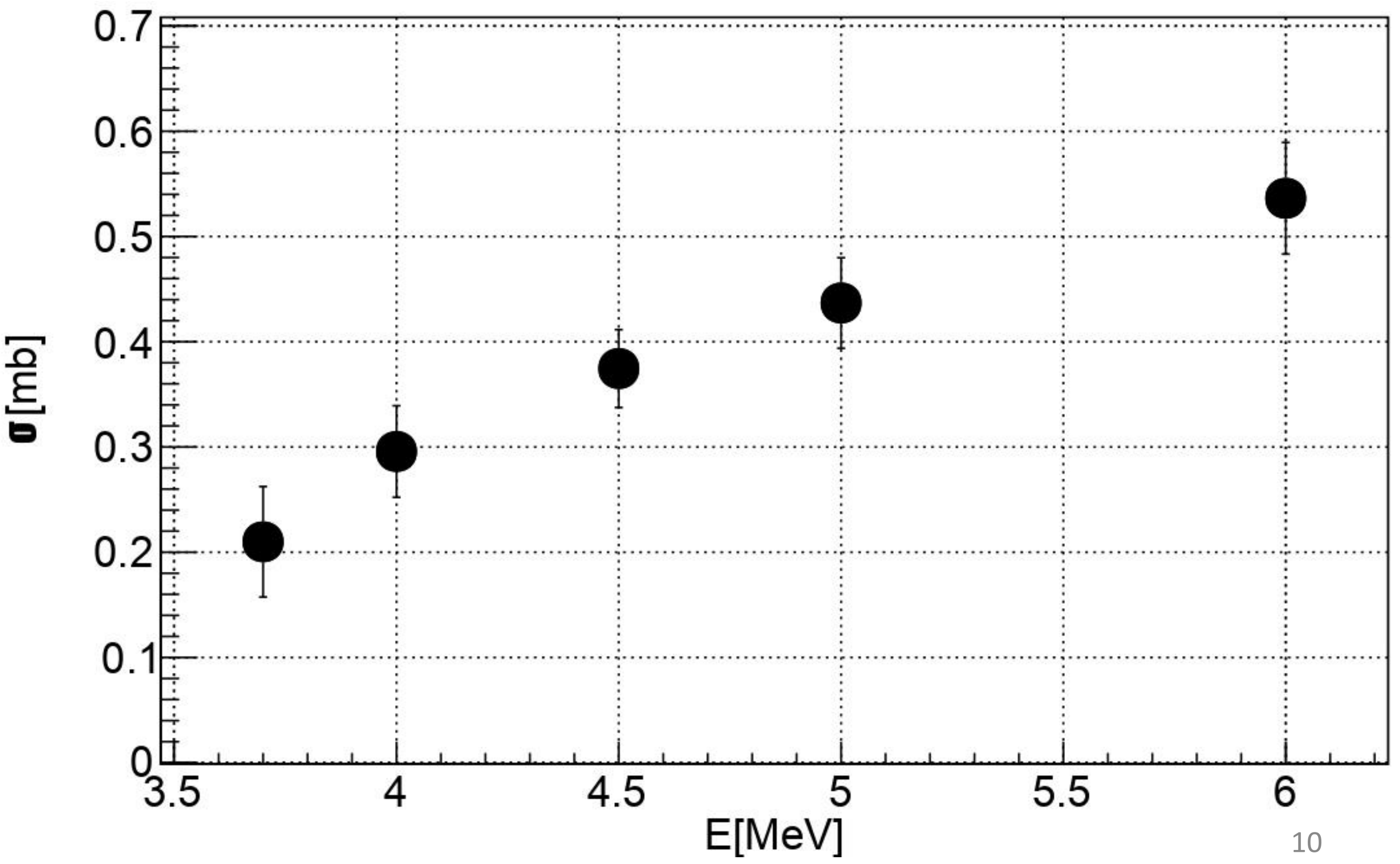
$N_b = I \cdot t$

$where\ I \sim 10^{7}\ s^{-1}$

$N_t \sim 10^{18}$

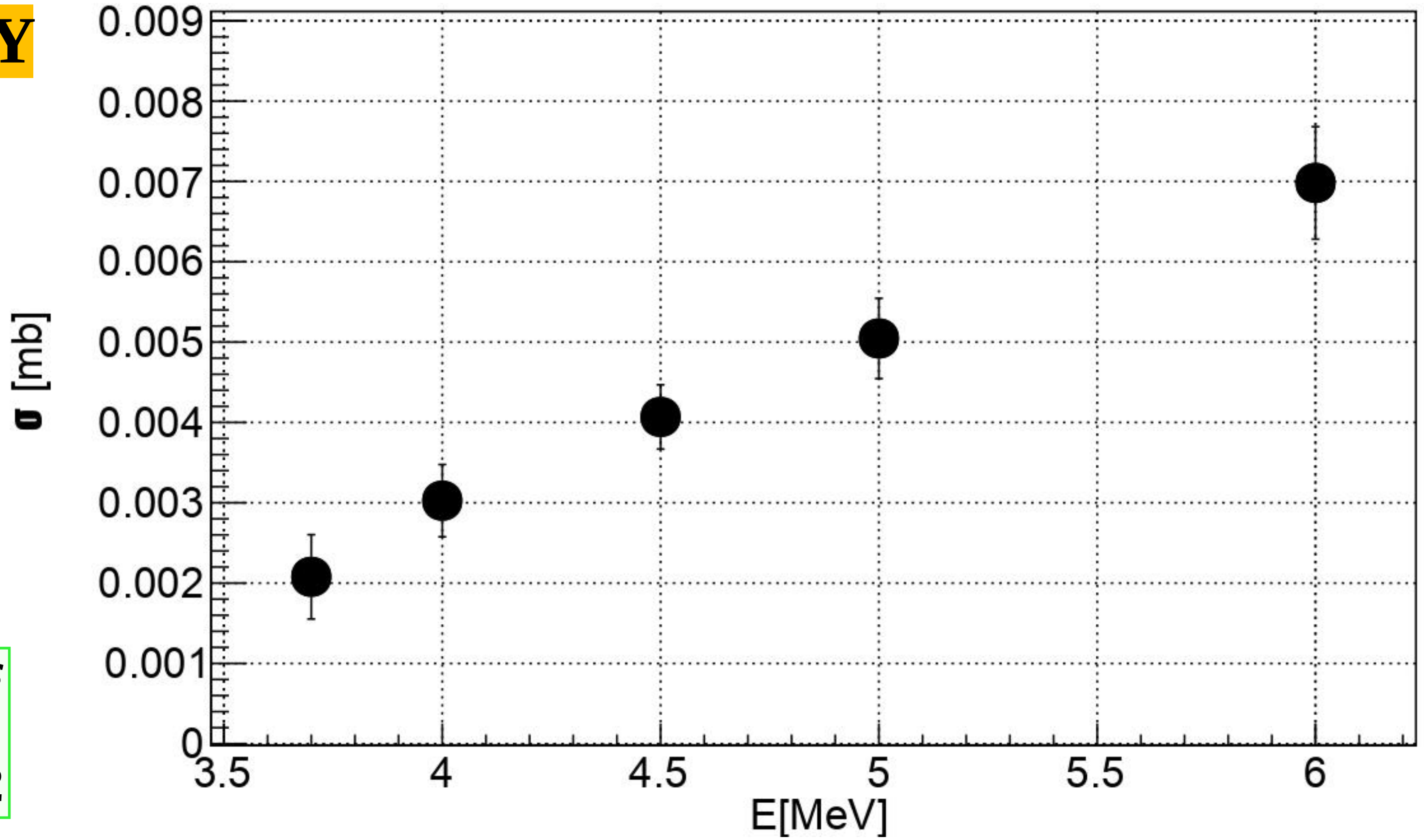
Quantity	Uncertainty
Events no	~ 5-18 %
Intensity	~ 10%
Li-7 atoms no	~ 1%
Efficiency	~ 1%

PRELIMINARY RESULTS



The ground state cross-section of the direct $^{3}H(\alpha,\gamma)\,^{7}Li$ reaction

PRELIMINARY RESULTS



PRELIMINARY RESULTS

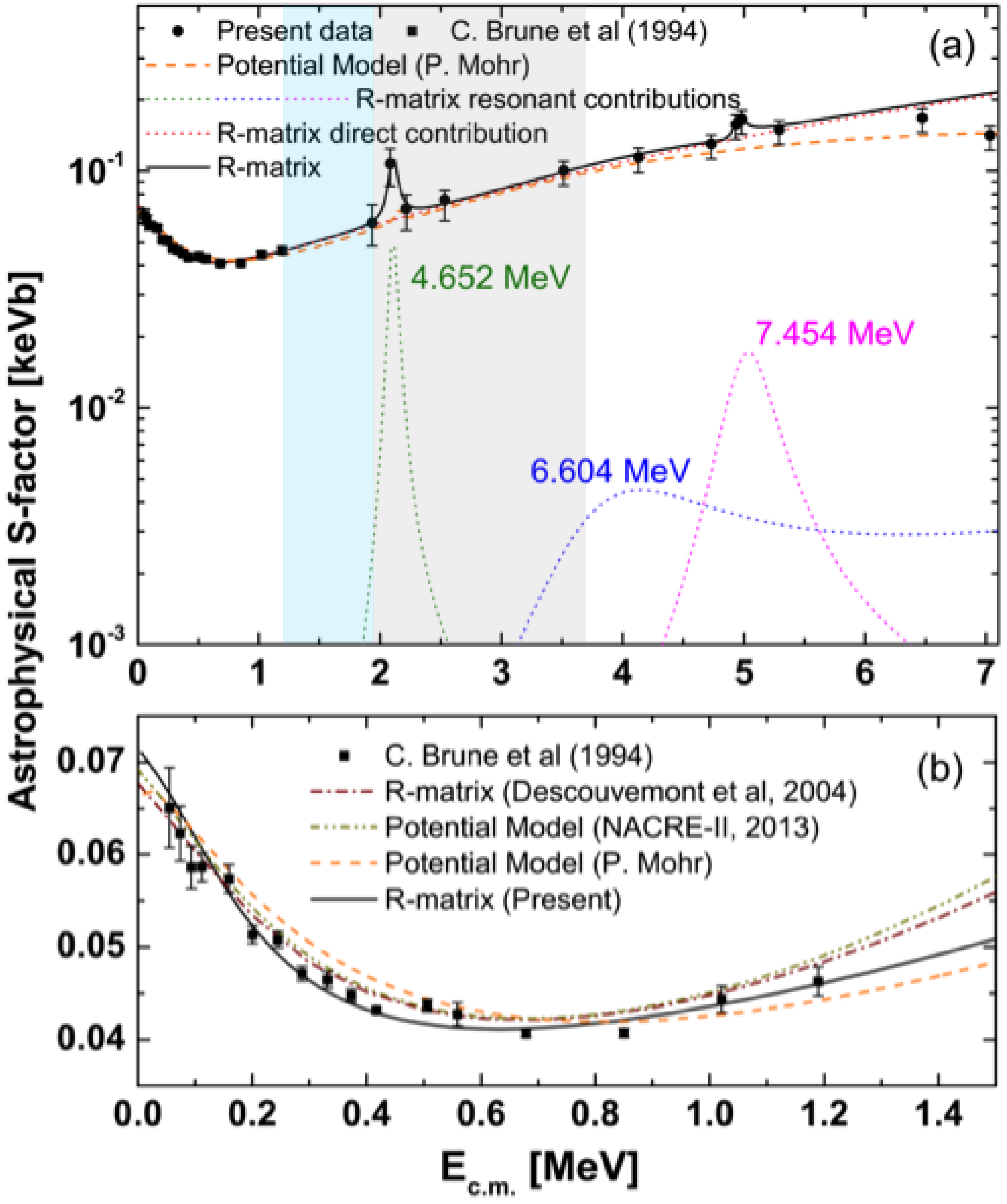
Ground state $\Rightarrow j = s$

Photons $\Rightarrow 2j + 1 = 2$

$E_{\alpha t} = E_\gamma - Q_{\alpha t \to 7Li\gamma}$

$Q_{\alpha t \to 7Li\gamma} = 1.397\ MeV$

$$\frac{\sigma_{7Li\gamma \to \alpha t}}{\sigma_{\alpha t \to 7Li\gamma}} = \frac{(2j_\alpha + 1)(2j_t + 1)}{2 \cdot (2j_{Li} + 1)} \cdot \frac{2 \cdot m_{\alpha t} \cdot E_{\alpha t} \cdot c^2}{E_\gamma^2} \cdot \frac{1}{1 + \delta_{\alpha t}} = \frac{1}{4} \cdot \frac{2 \cdot m_{\alpha t} \cdot E_{\alpha t} \cdot c^2}{E_\gamma^2}$$

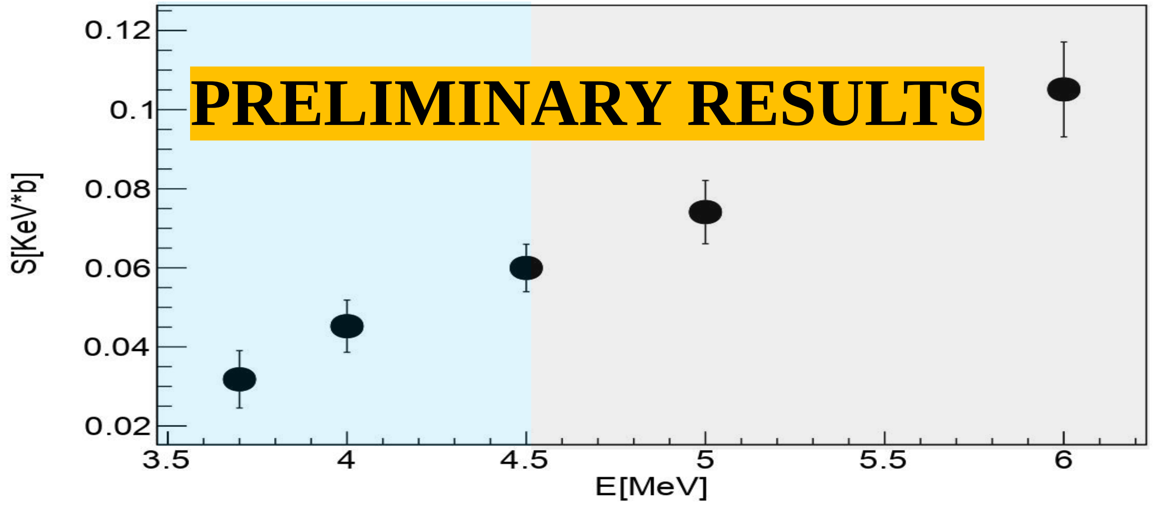


Astrophysical S – factor

$$S_{\alpha t\to 7Li\gamma}(E) = e^{2\pi\eta} \cdot E \cdot \sigma_{\alpha t\to 7Li\gamma}(E)$$

$$0.989534 \cdot Z_\alpha Z_t \sqrt{\frac{1}{E} \cdot \frac{M_\alpha M_t}{M_\alpha + M_t}}$$

Measurement of the $^7Li(\gamma,t)\,^4He$ ground-state cross section between $E_\gamma =$ 4.4 and 10 MeV, M. Munch, C. Matei, S.D. Pain, K.A. Chipps, et al., ***Phys. Rev. C 101, 055801 (2020)***



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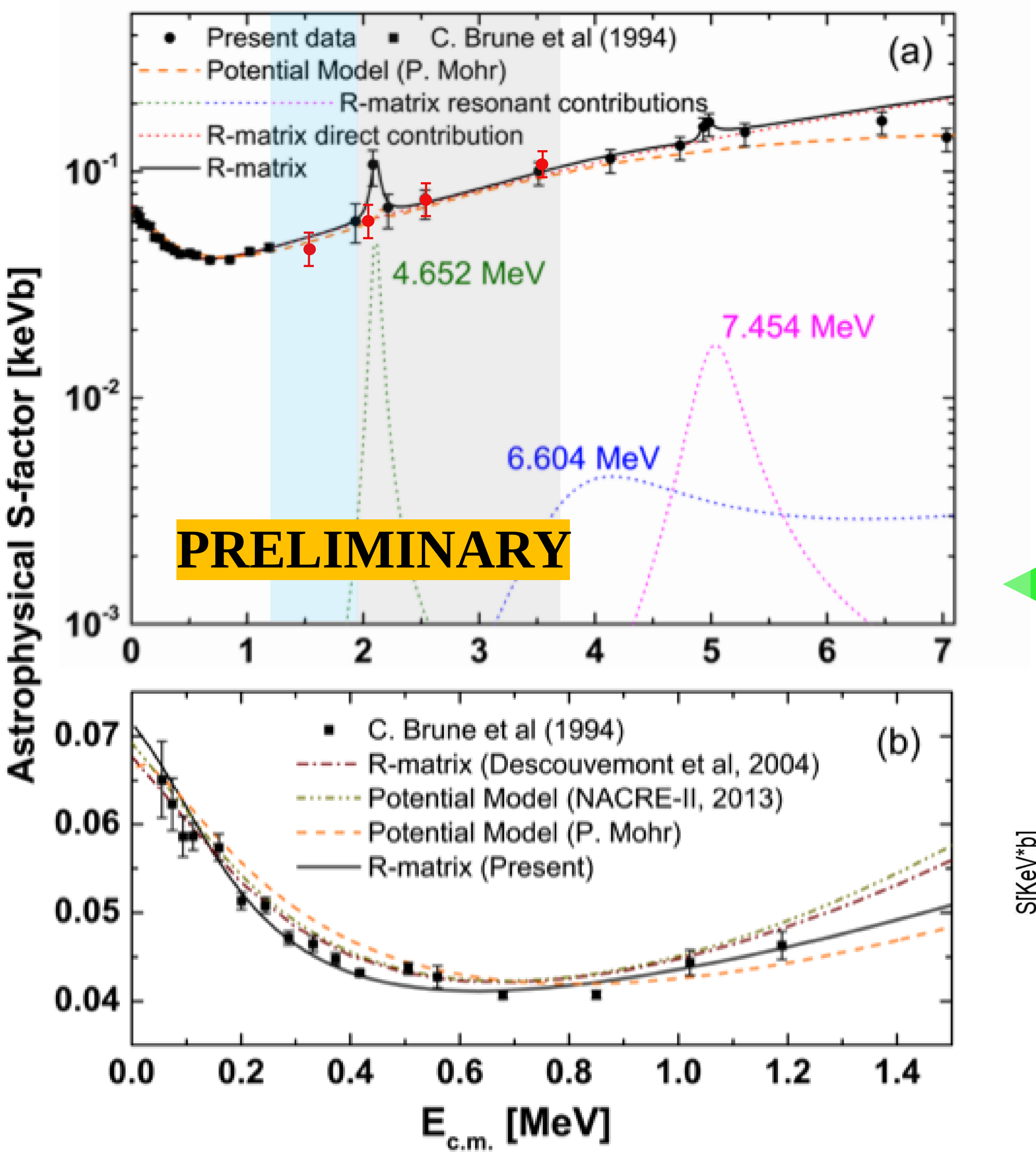

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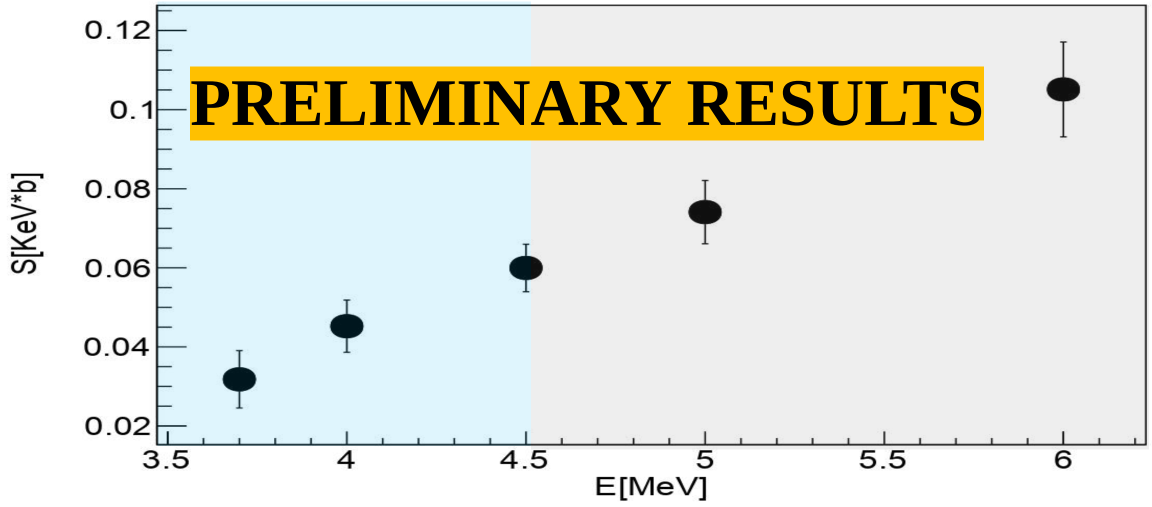

CONCLUSIONS…

- **The reaction $^{3}H(\alpha,\gamma)\,^{7}Li$ contributes to the production of ^{7}Li in Universe** and it’s measurement is important due to the discrepancy between the theoretical models and the experimental data.

- **The direct reaction was studied in 1994** by Brune et al for gamma rays energies below 3.7 MeV, but such a measurement cannot be performed anymore.

- **The inverse reaction has been studied in 2017** by our team at HIgS for gamma beam energies between 4.4 and 10 MeV using a Silicon Detector Array. Below 6 MeV the coincidences were clearly observed only in the thinner detectors.

- **A new experiment was performed in April 2023 to cover the gap between 3.7 and 6 MeV.** The set-up was improved by using an array of thinner silicon detectors, by decreasing the thickness and the electron density of the entry flange and by using a longer pipe.

✓ **The coincidences have been clearly separated and the background has been highly reduced, affecting only the lowest energy. Data analysis underway. The preliminary ground state cross-section and the s-factor have been successfully extracted.**

Thank you!

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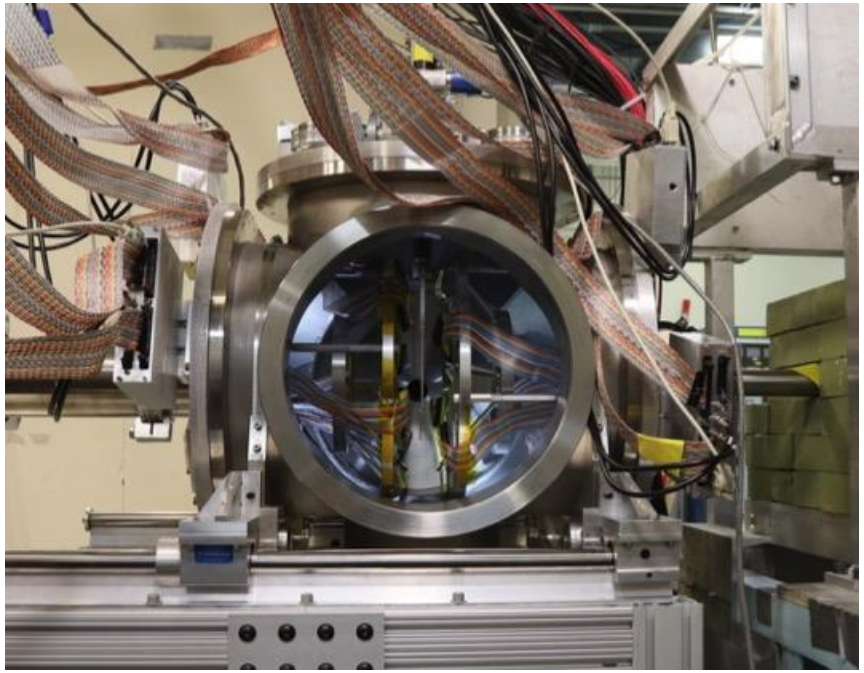
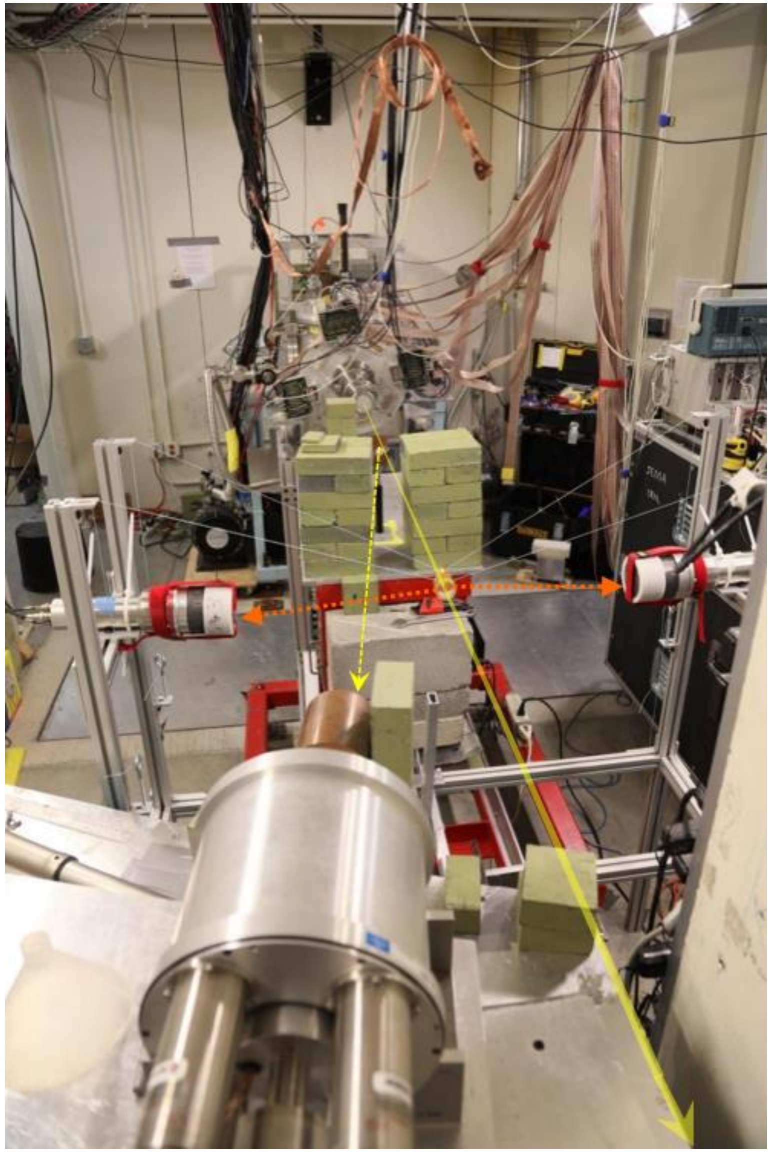
- *M. Grinder, S. Balakrishnan, Heather Garland, Jolie Cizewski (Rutger University - New Brunswick, New Jersey, USA)*
- *H. Karwowski, R.V. Janssens, T. Psaltis, C. Marshall (University of Nord Carolina - Chapel Hill, Nord Carolina USA)*
- *C.R. Brune, A. Voinov (Ohio University, Athens, Ohio, USA)*
- *O. Tindle, C. Haverson, R. Smith (Shefield Hallam University, UK)*
- *M. La Cognata, G.L. Guardo, S. Palmerini, L. Sergi, D. Lattuada, R.G. Pizzone, G. Rapisarda, A. Tumino (INFN-Laboratori Nazionali del Sud, Catania, Italy)*
- *K.Y. Chae, Gyoungmo GU (Sungkyunkwan University, Suwon, Korea)*

Set-up at HIγS

Mounting detectors



Vacuum chamber for charged-particle detection



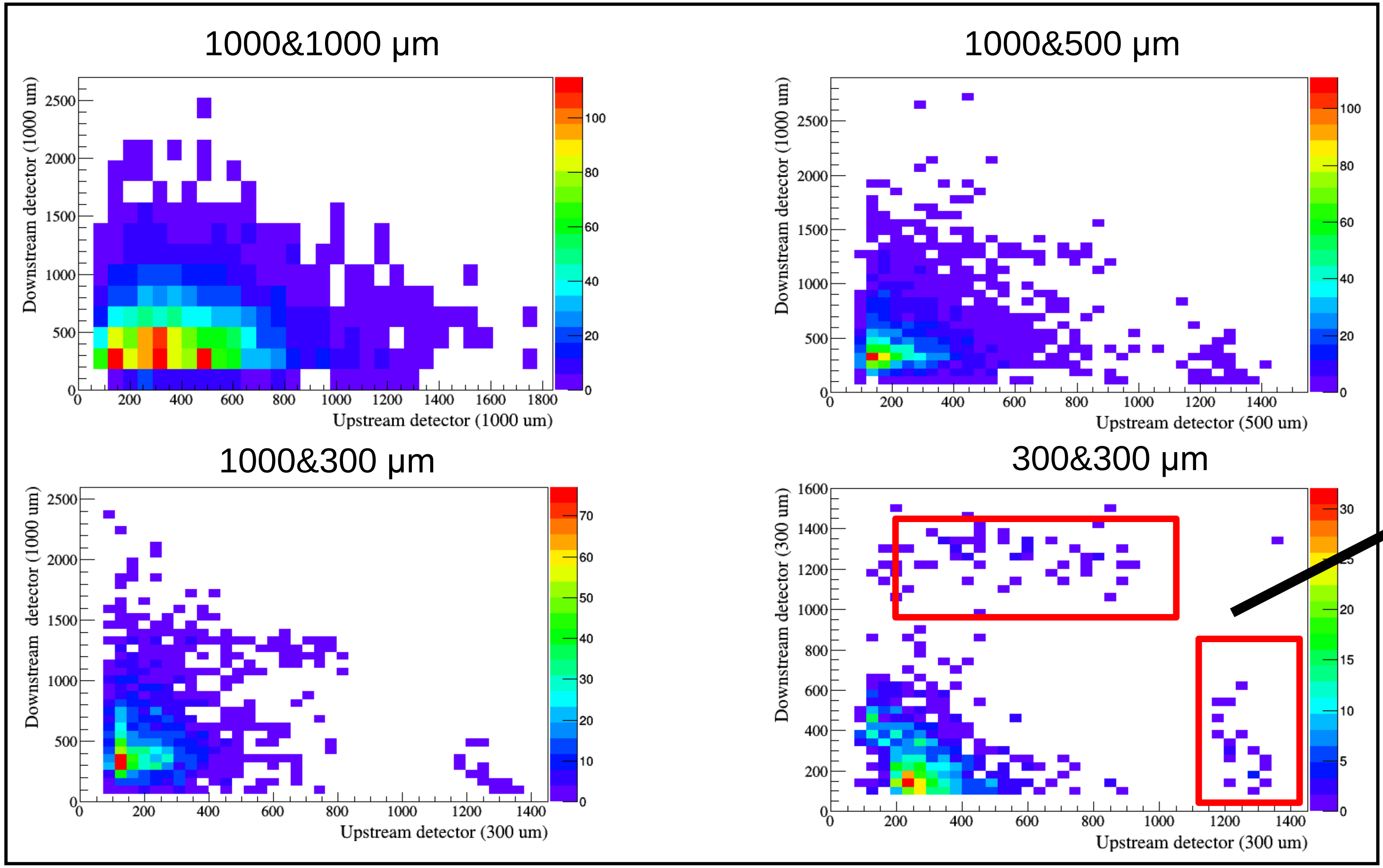
Beam diagnostics

The old experiment:
2017
4.4 MeV - 10 MeV

$\leftarrow {}^{7}Li(\gamma,t)^{4}He \rightarrow$

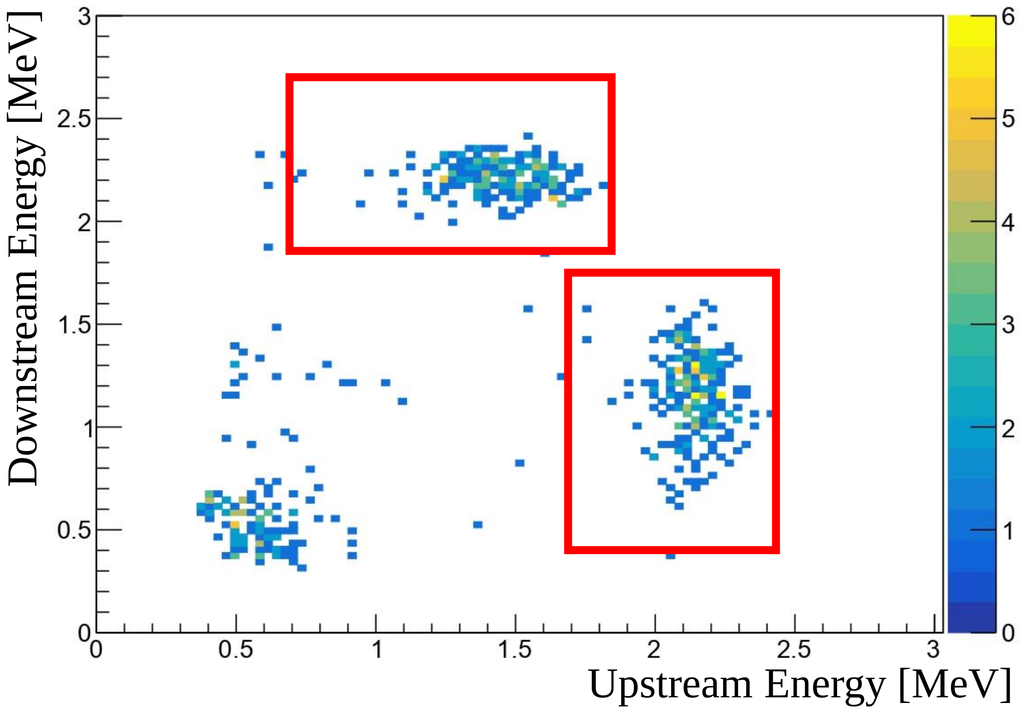
The new experiment:
6th April 2023-12th April 2023
3.7 MeV - 6 MeV

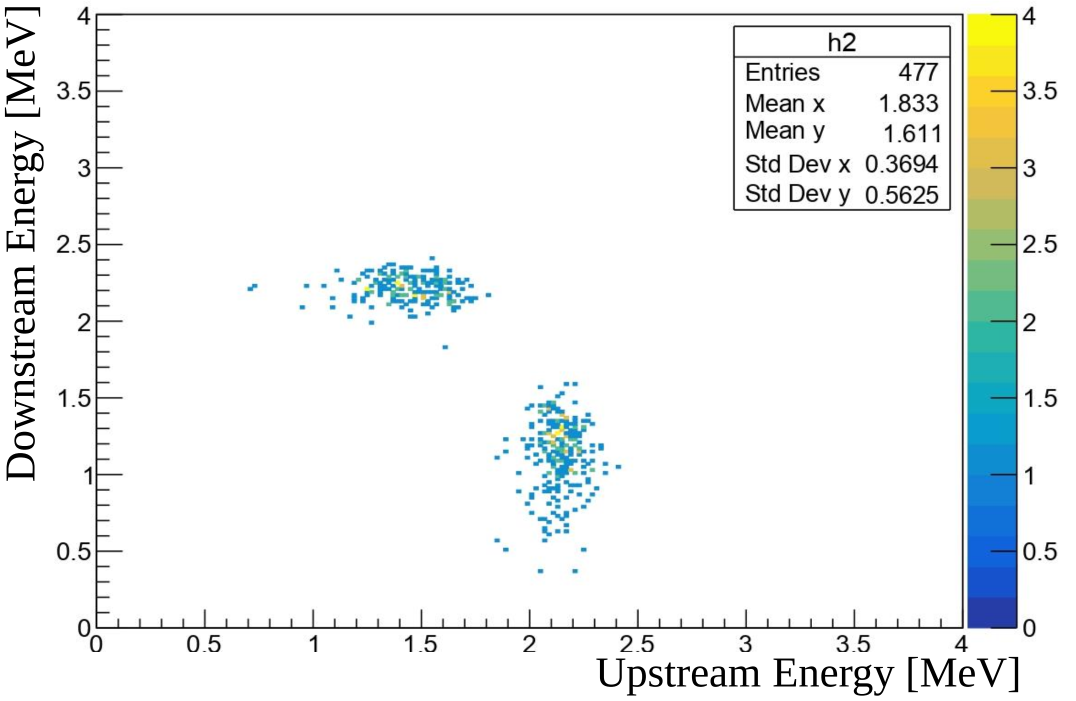
HIγS Laboratory of Duke University (USA), 2017



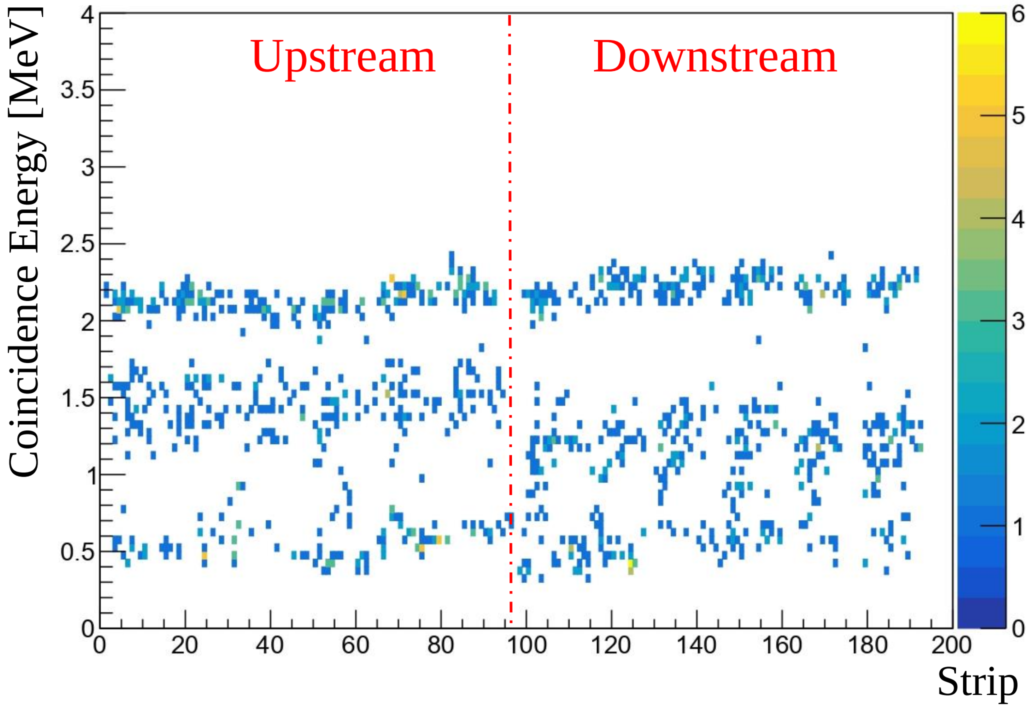
The coincidences were clearly separated for energies higher than 6 MeV

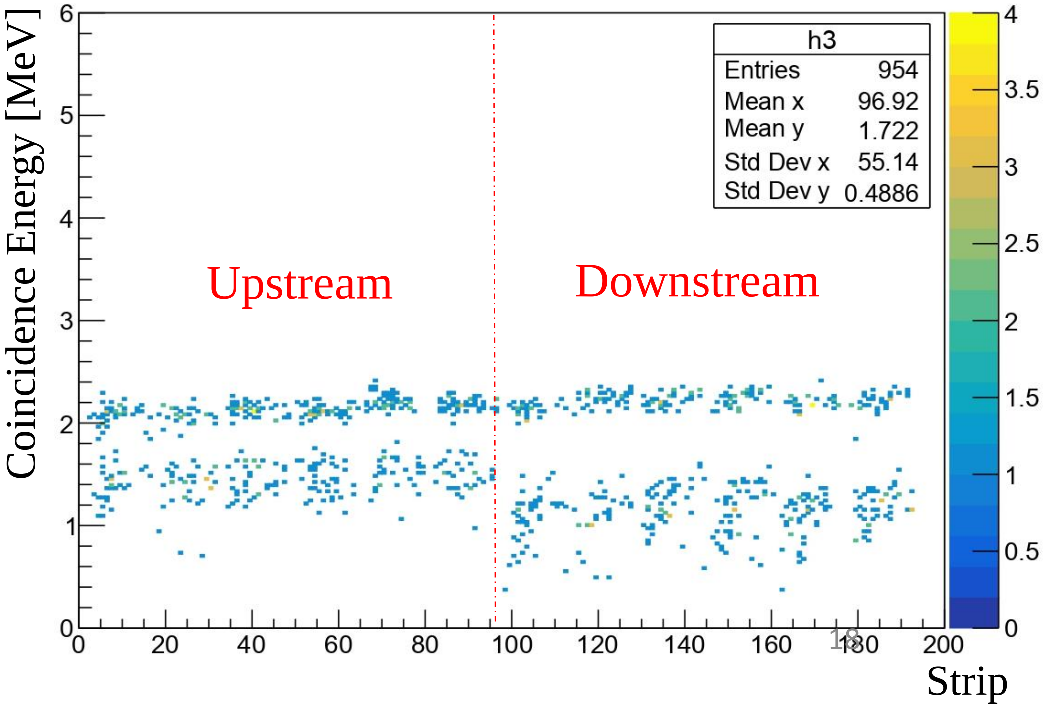
Coincidences corresponding to 4.4 MeV gamma beam were observed only in the thinner detectors

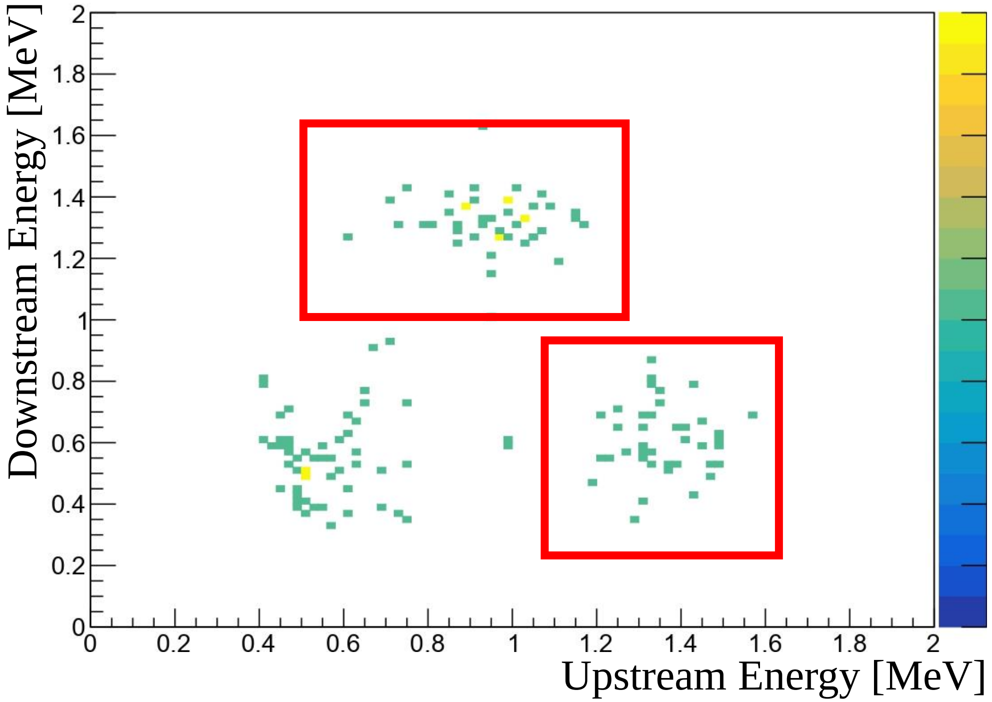


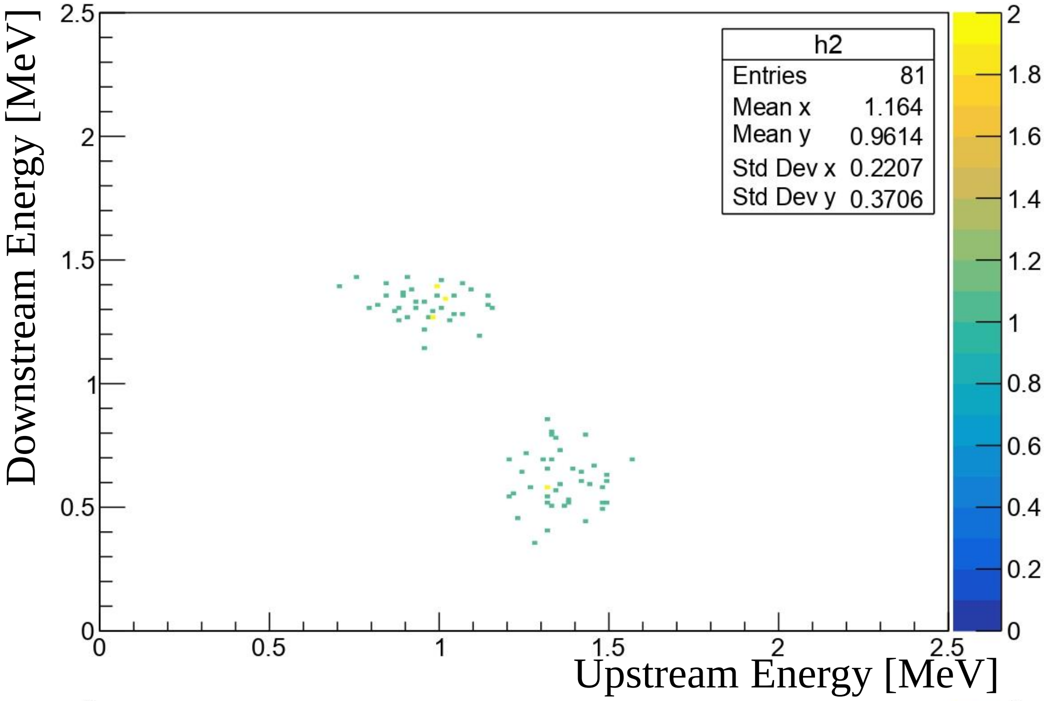


Background can be easily subtracted for **6 MeV**

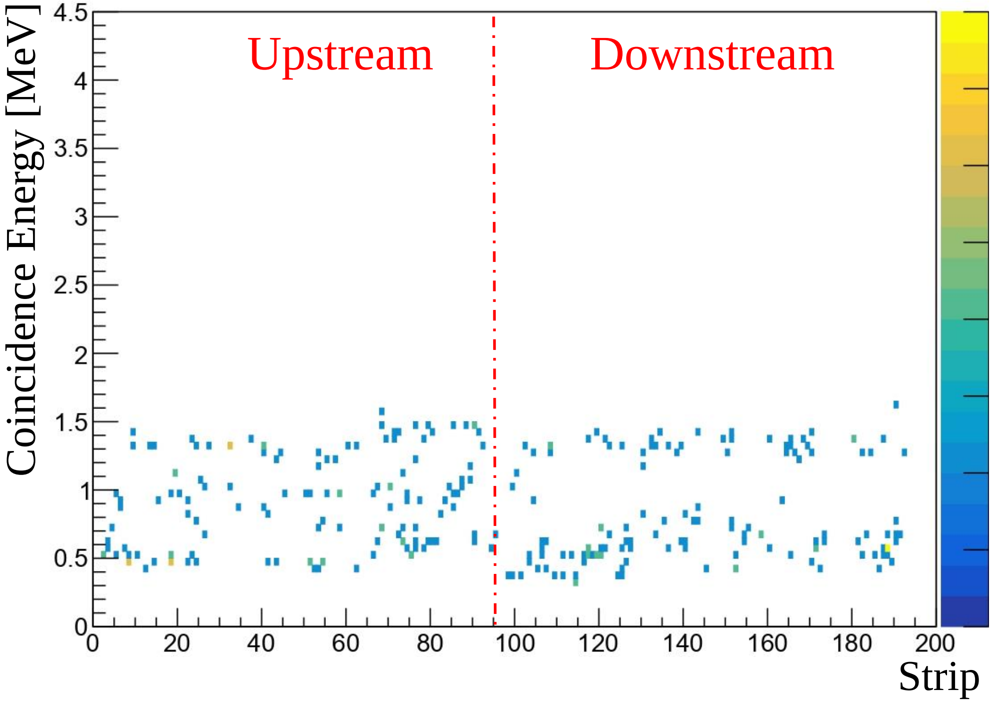


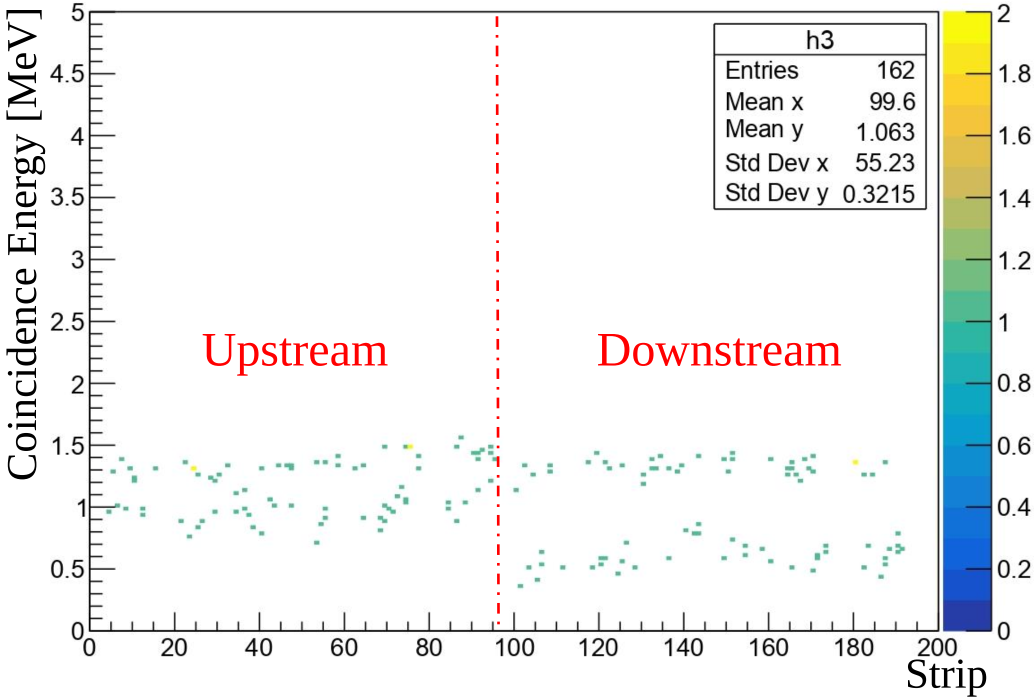


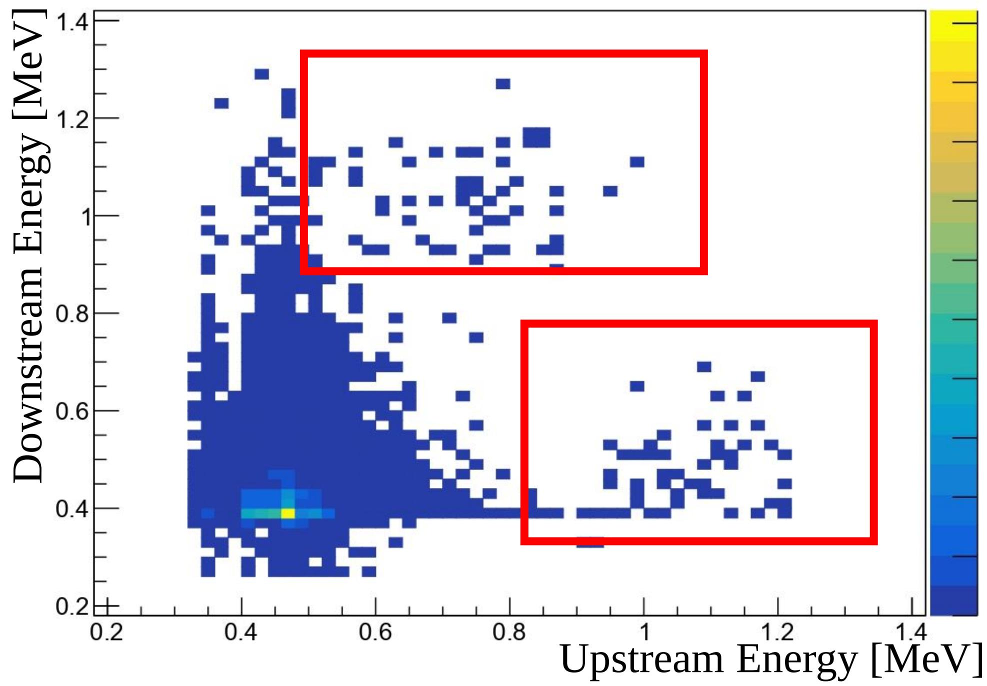


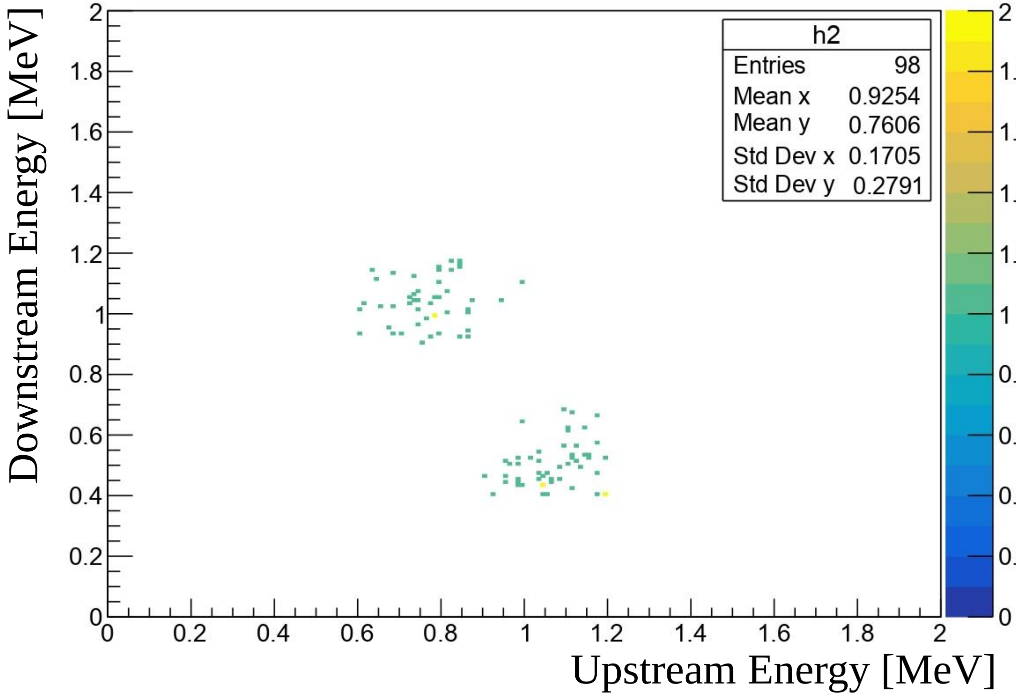


And
even
for
4.5 MeV

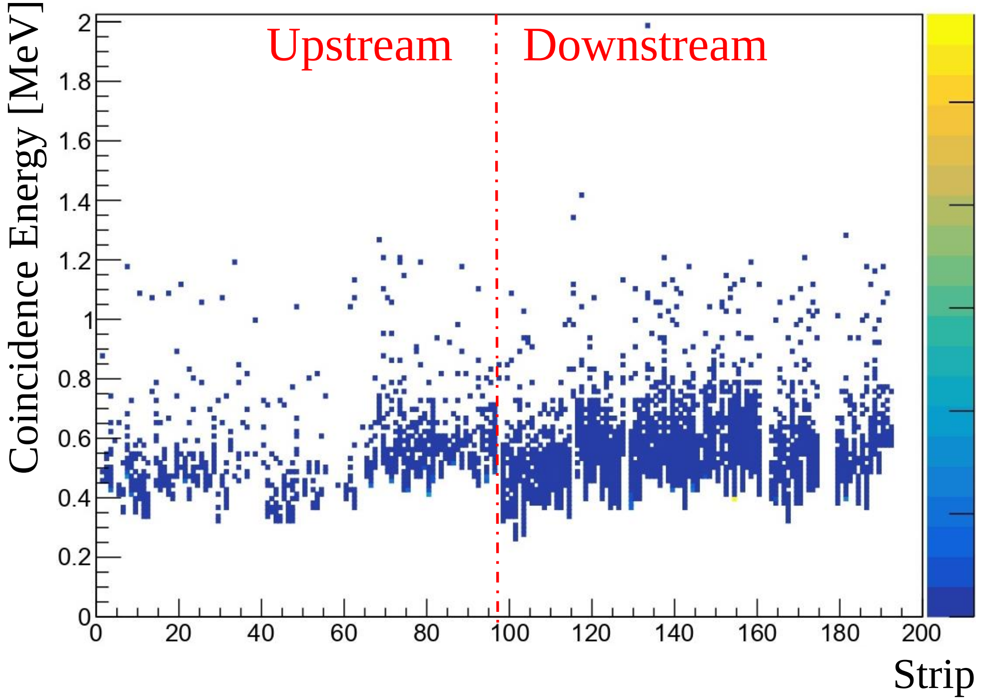


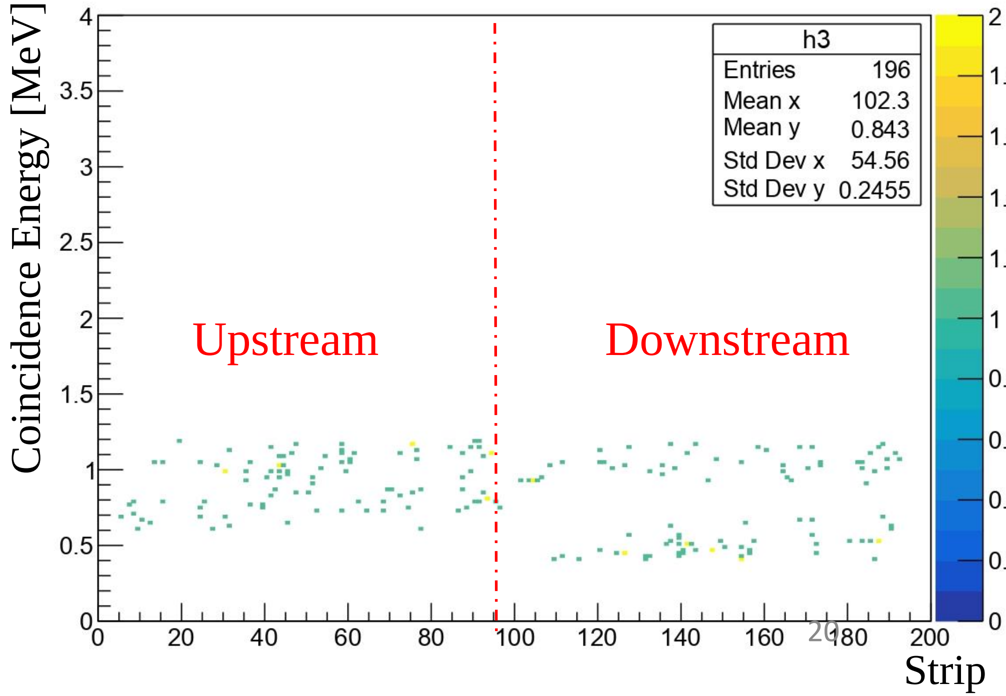


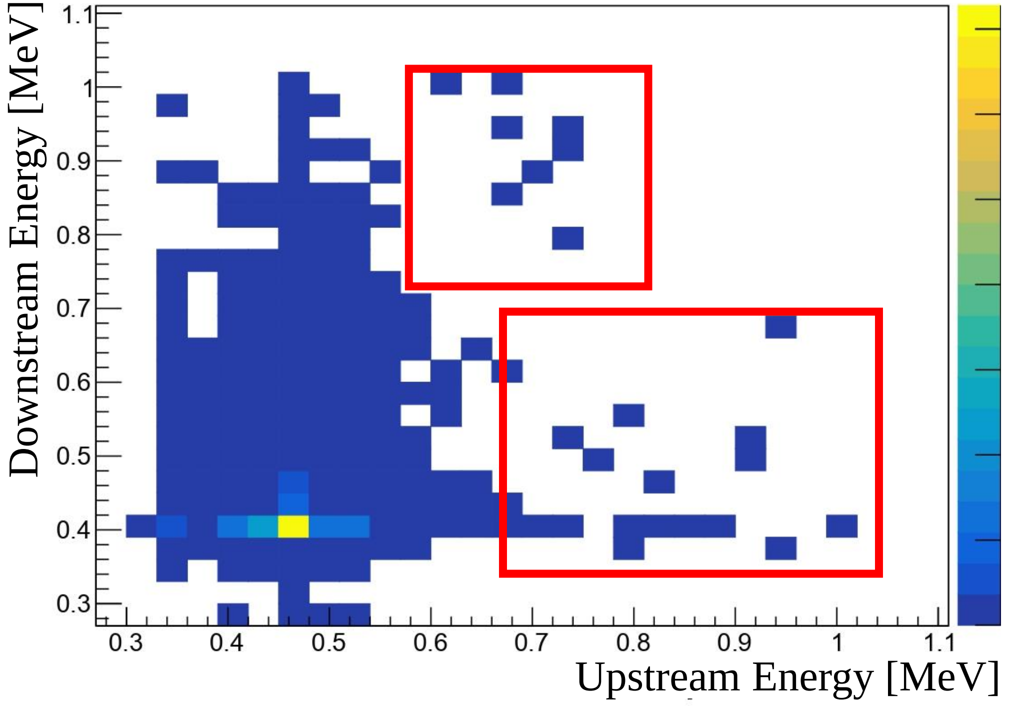


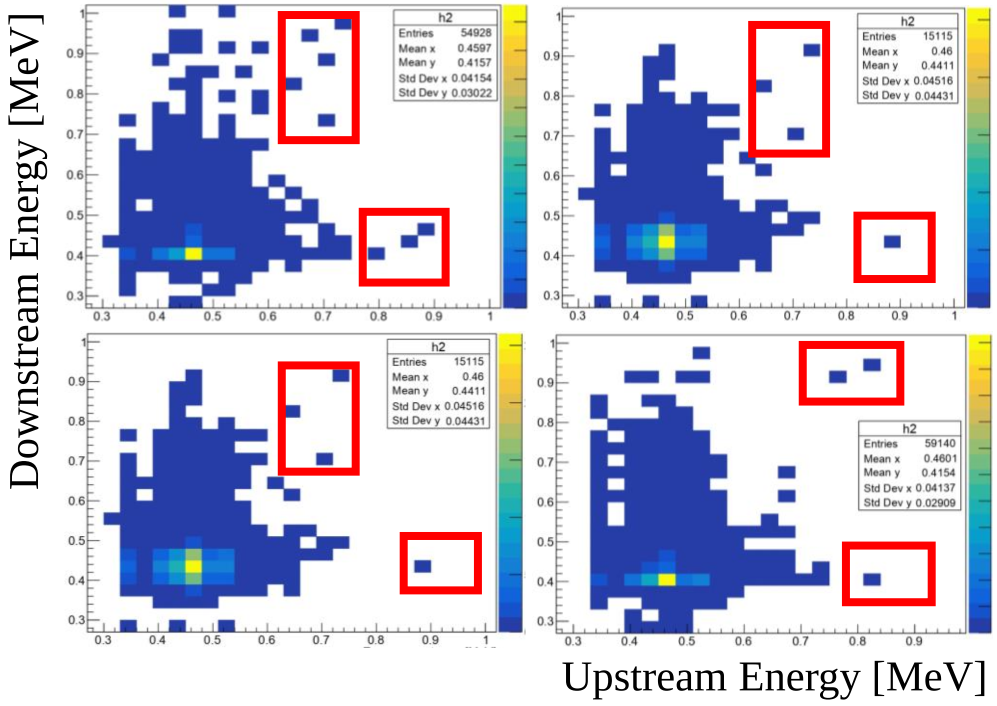


Still possible for **4 MeV**

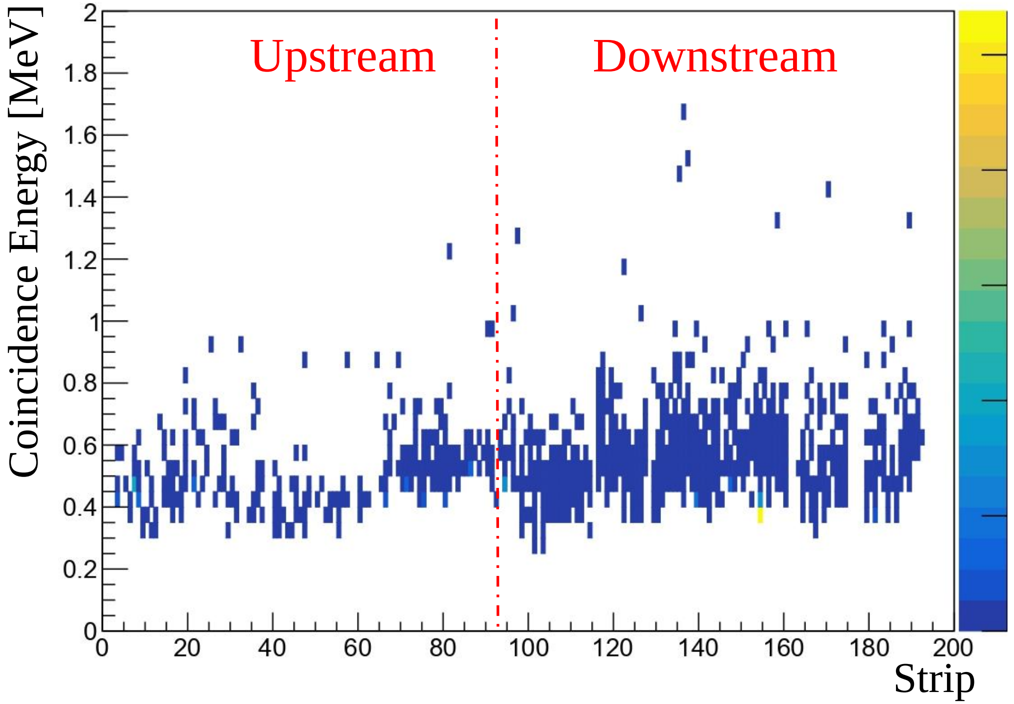


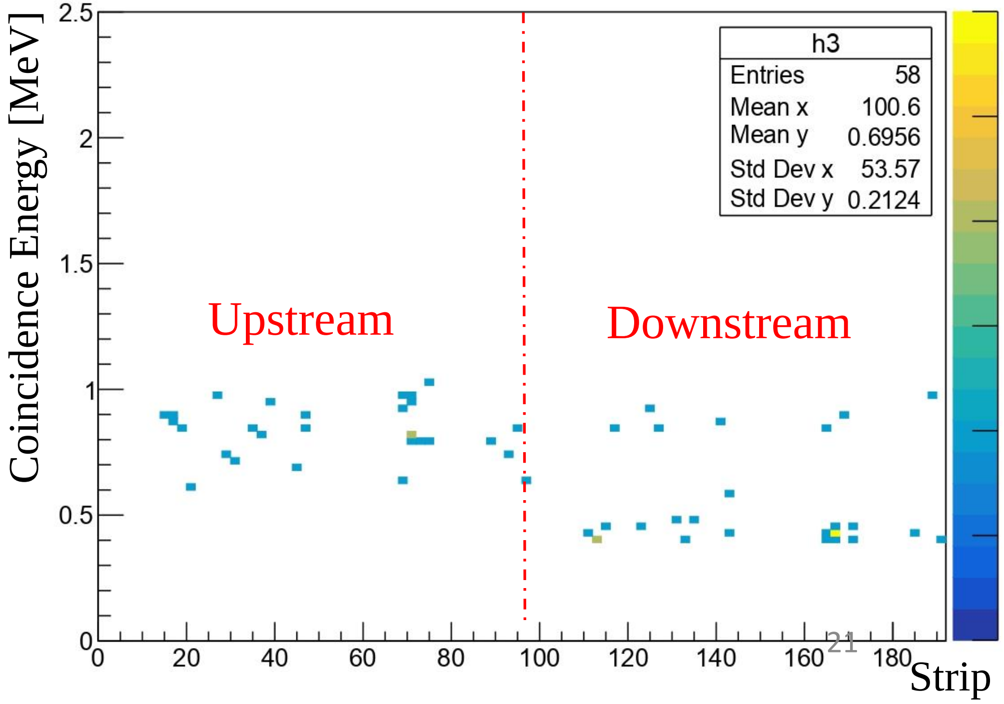




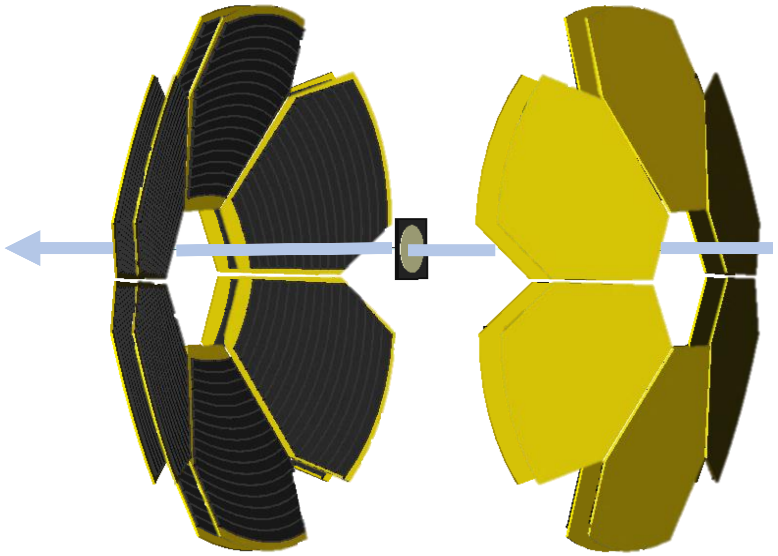


Difficult to distinguish for **3.7 MeV**





p – process

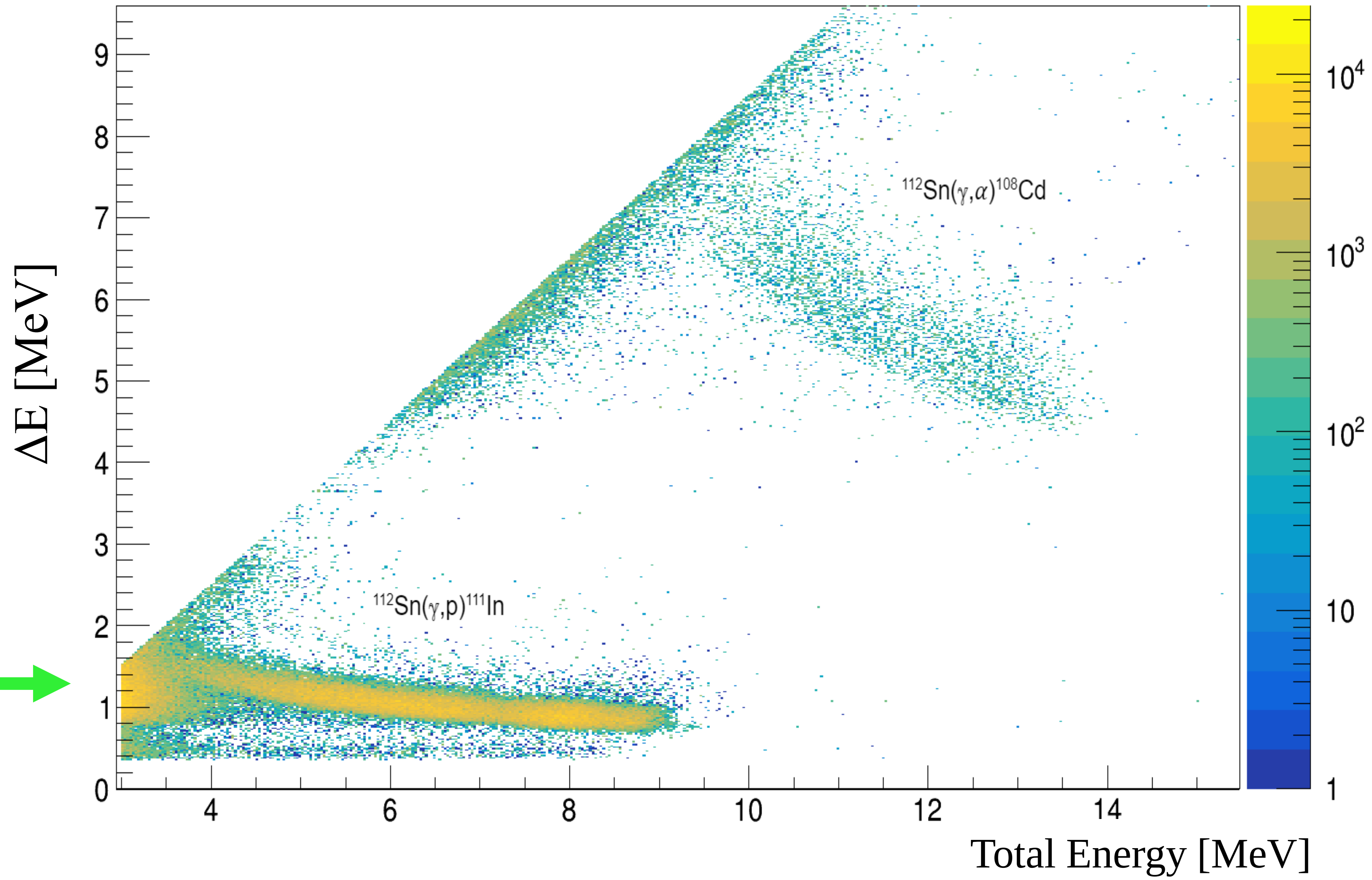


$^{102}Pd(\gamma,p)^{101}Rh$

$^{102}Pd(\gamma,\alpha)^{98}Ru$

$^{112}Sn(\gamma,p)^{111}In$

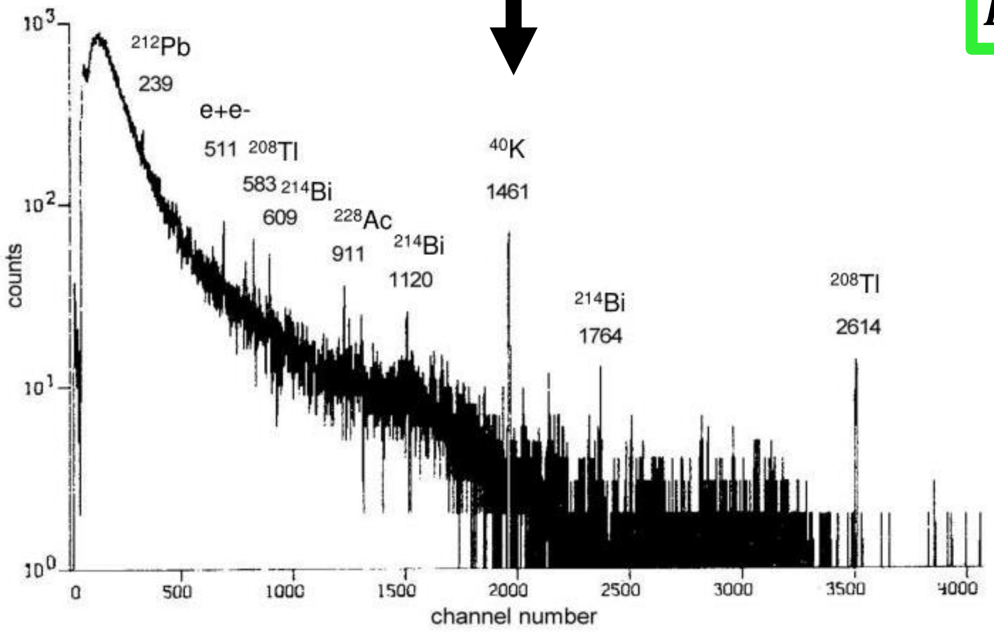
$^{112}Sn(\gamma,\alpha)^{108}Cd$



Gamma beam energy measurement

Ge DETECTOR + ATTENUATORS

Calibrated using background

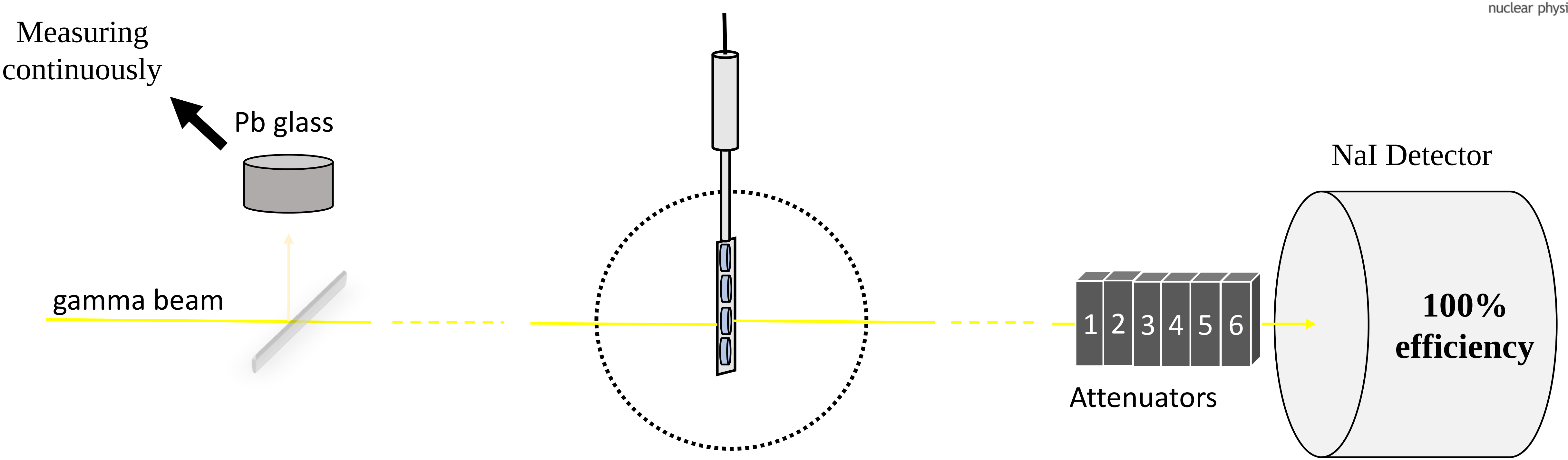


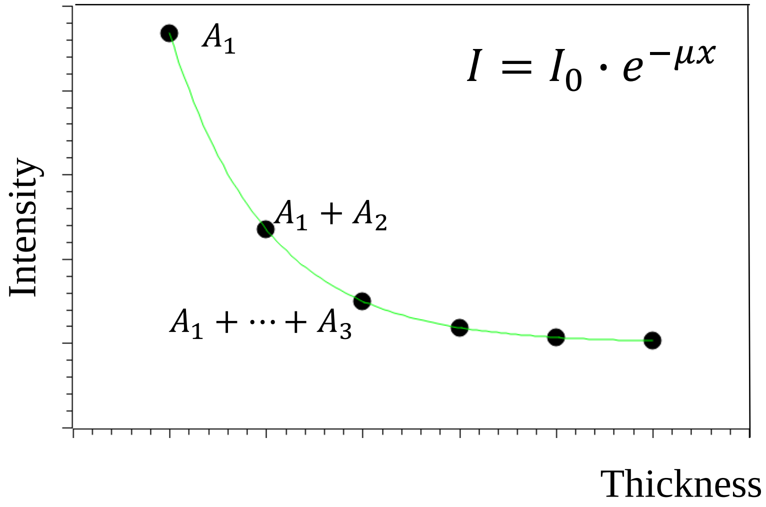
$$E_\gamma = E_{det} + E_{loss}$$

Known energy loss

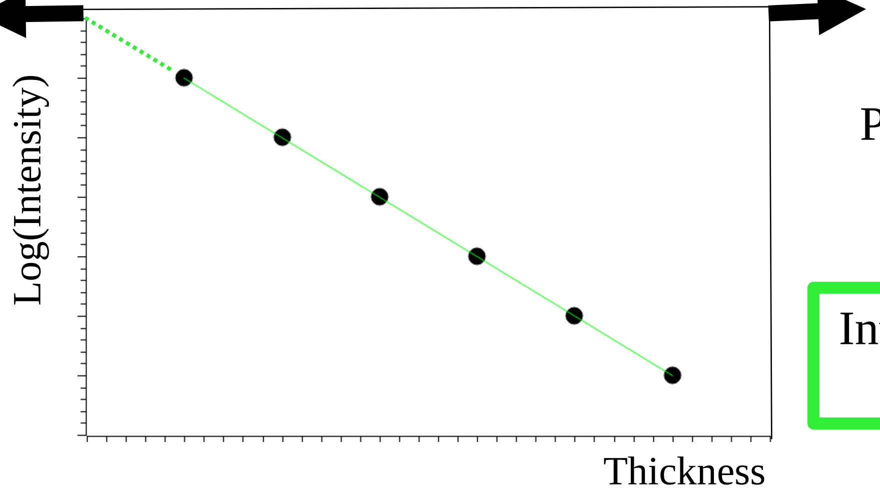
39.35 cm
of
copper

Gamma beam intensity measurement





No Attenuation Value

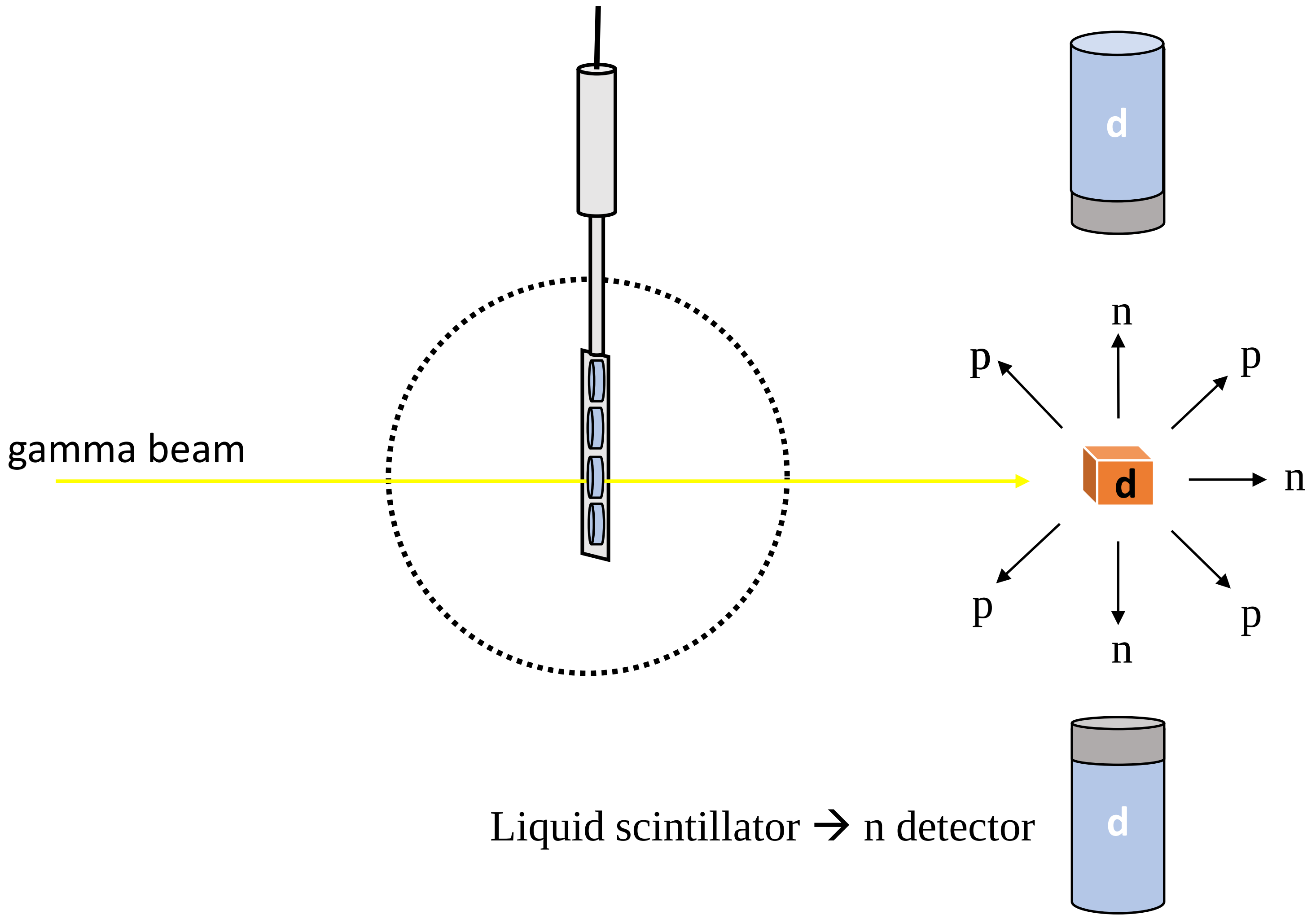


Coefficient related to the energy of the beam

Pb glass intensity calibration

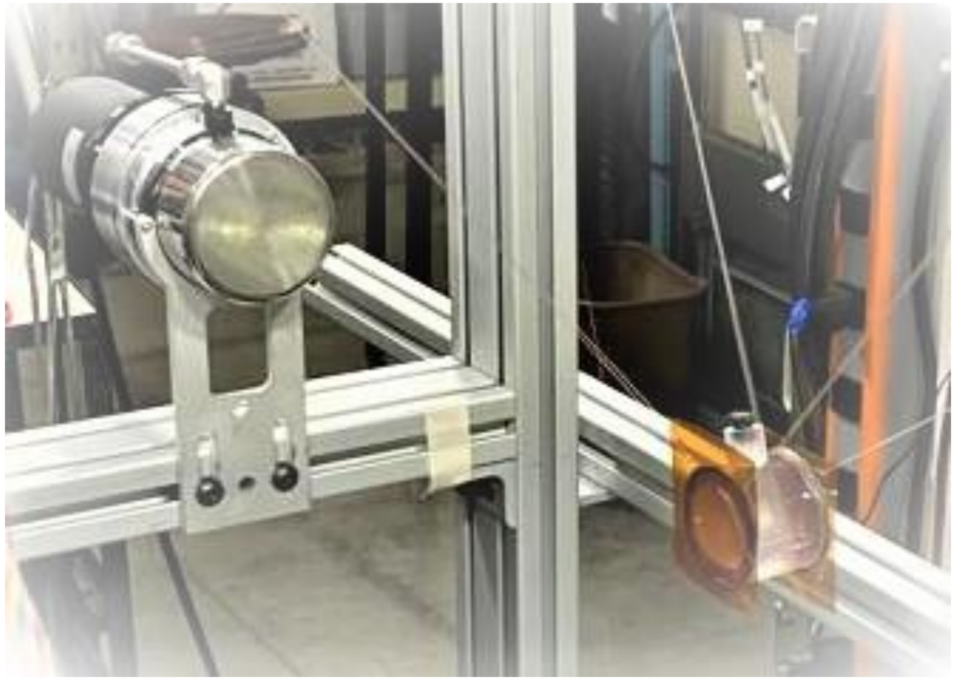
Intensity measurement during the run

Gamma beam intensity measurement



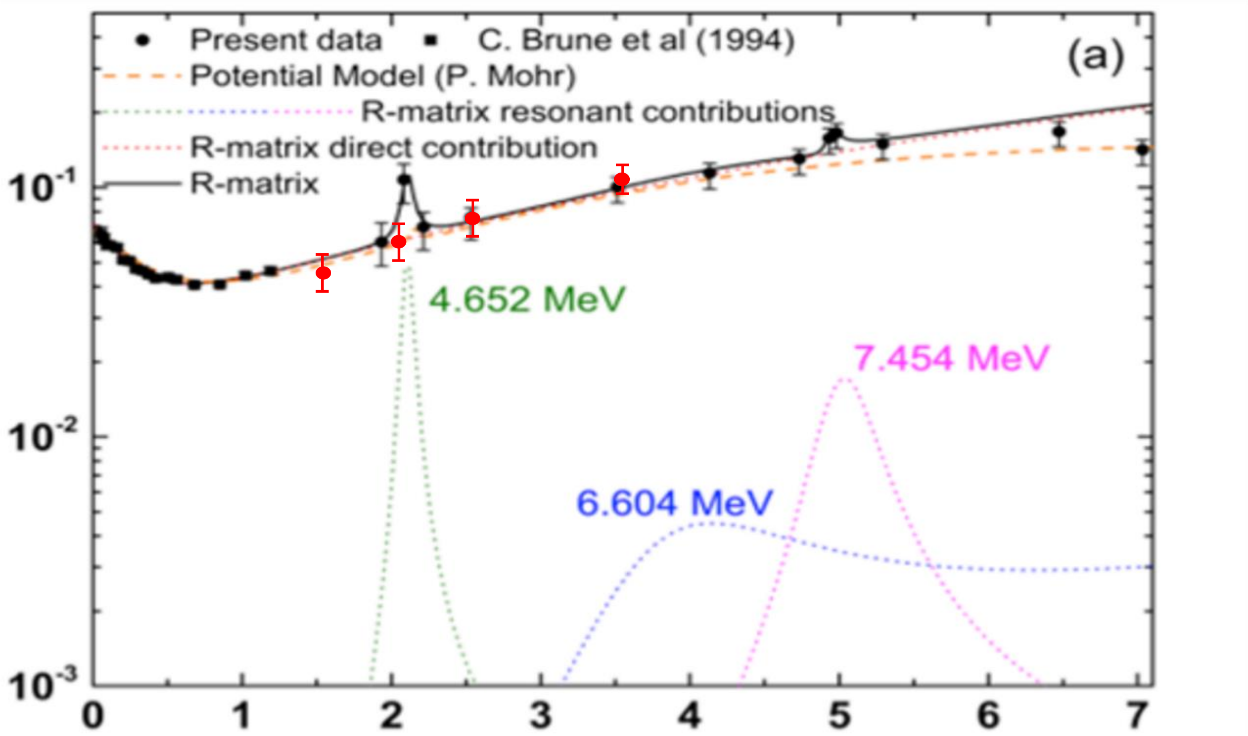
deuterium photodisintegration

$$d + \gamma = n + \mathrm{p} + 2.2\ \mathrm{MeV}$$



$$E_n = \frac{E_{gamma} - 2.2\ MeV}{2}$$

$$Nr\ of\ neutrons:$$
$$\varepsilon n = \ \sigma_{photodis} \cdot N_d \cdot I_\gamma$$



Present data
C. Brune et al (1994)
(a)
Potential Model (P. Mohr)
R-matrix resonant contributions
R-matrix direct contribution
R-matrix
4.652 MeV
7.454 MeV
6.604 MeV
10^-1
10^-2
10^-3
0
1
2
3
4
5
6
7