The study of the $^{7}Li(\gamma, \alpha)\,^{3}H$ reaction for energies below 6 MeV at HIγS

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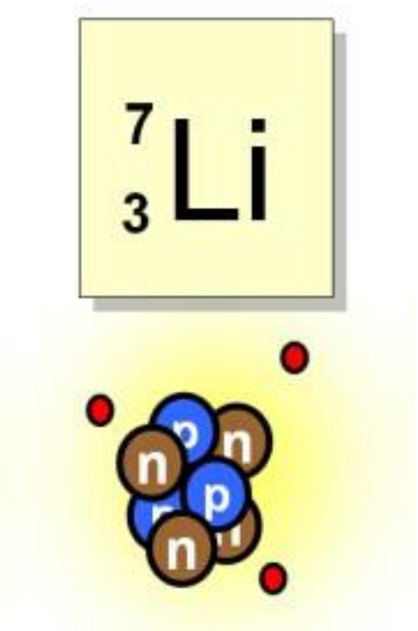
Nuclear Physics in Astrophysics IX
17.09.2024

Motivation of the experiment

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

“Cosmological Li problem”:

$^{7}\boldsymbol{Li}$ **abundance is 3-4 times lower than expected** ← Observations on the low-metallicity stars



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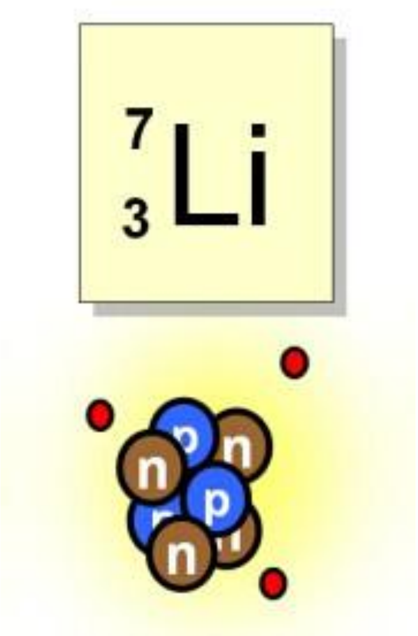

- The stellar measurements are leading to anomalous results

OR

- An error is present in the nuclear theoretical models

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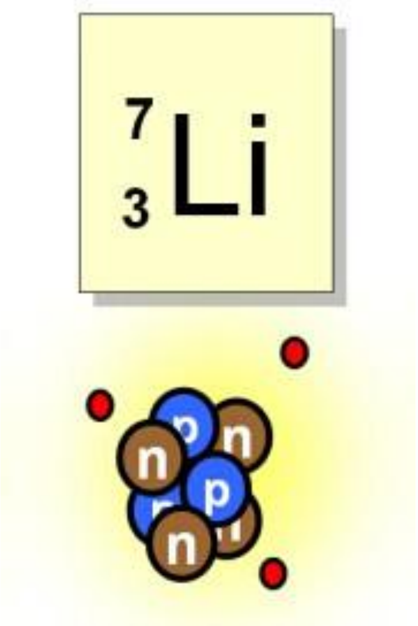


- The stellar measurements are leading to anomalous results

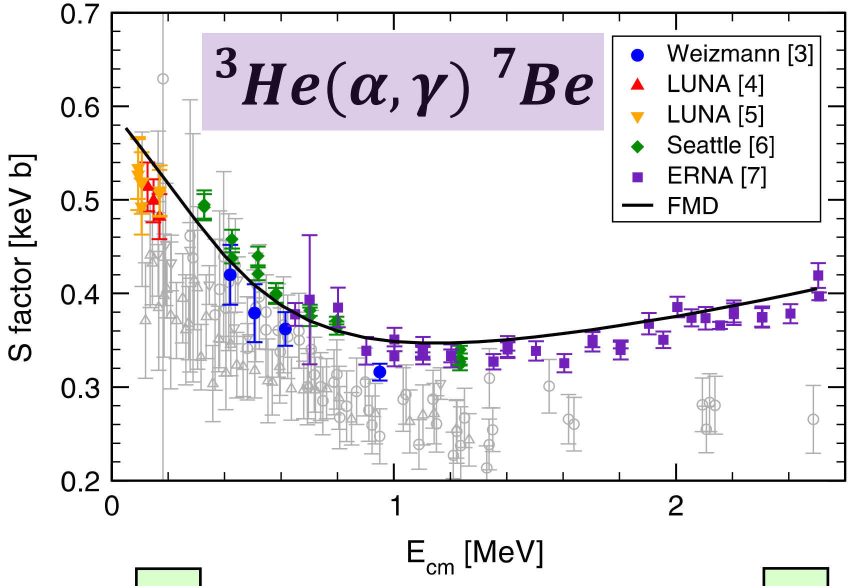
OR

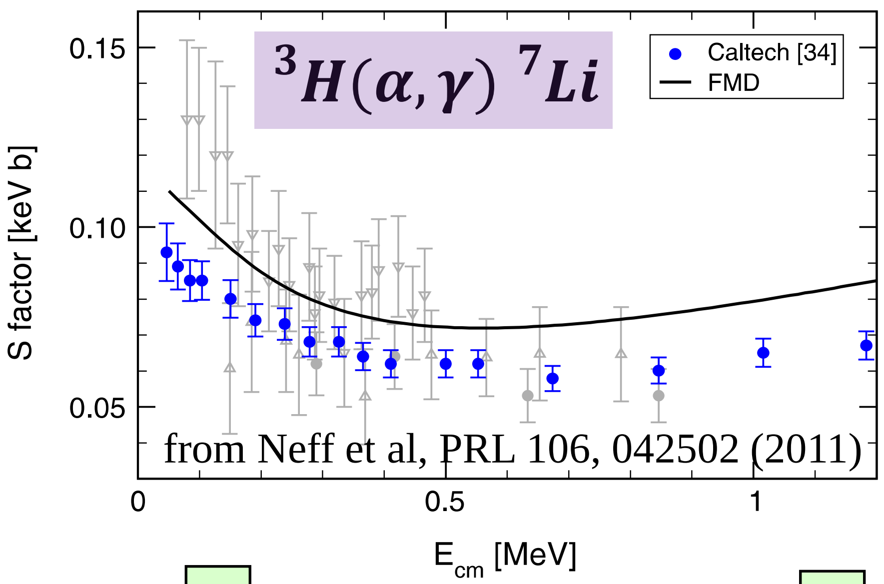
- An error is present in the nuclear theoretical models

The error can be related to the WMAP baryonic density

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

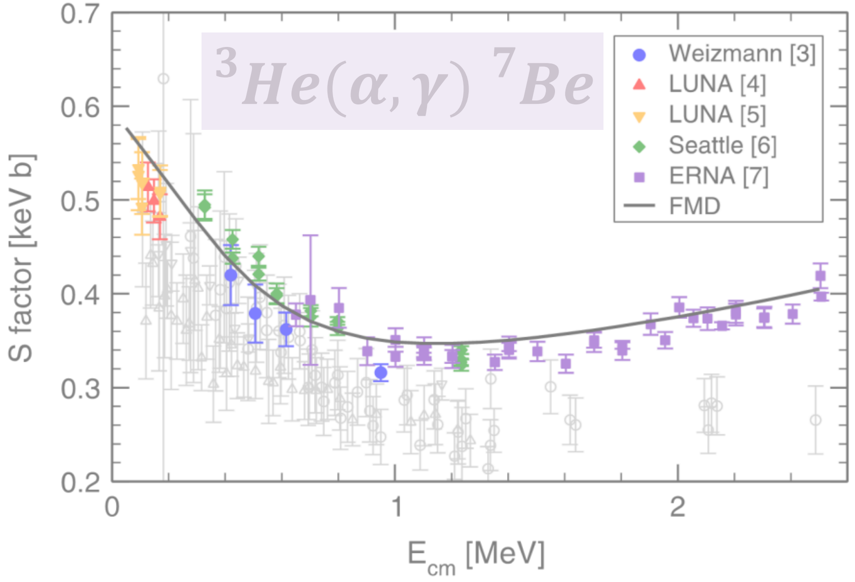
Two main reactions are responsible for the production of mass 7 elements

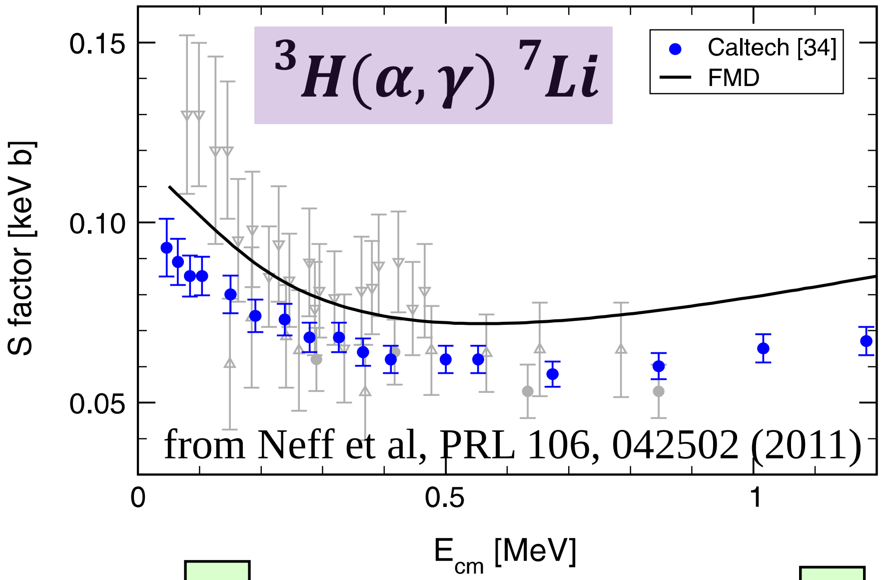




The theoretical models doesn't fit the experimental data for $^{3}H(\alpha,\gamma)\ ^{7}Li$

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





Only a few experiments were performed

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

However, the $^3H(\alpha,\gamma)\ ^7Li$ 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: $2j_\gamma + 1 = 2$

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Direct reaction

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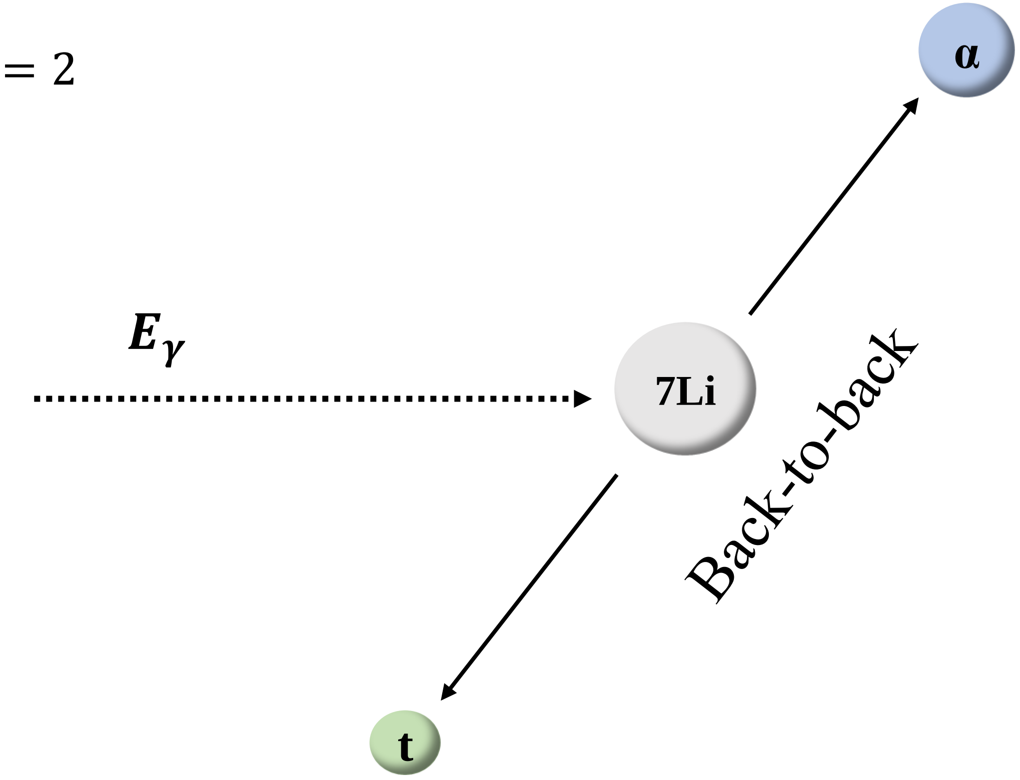
$\boldsymbol{{}^{3}H(\alpha,\gamma)\,{}^{7}Li}$ ➡ Direct reaction

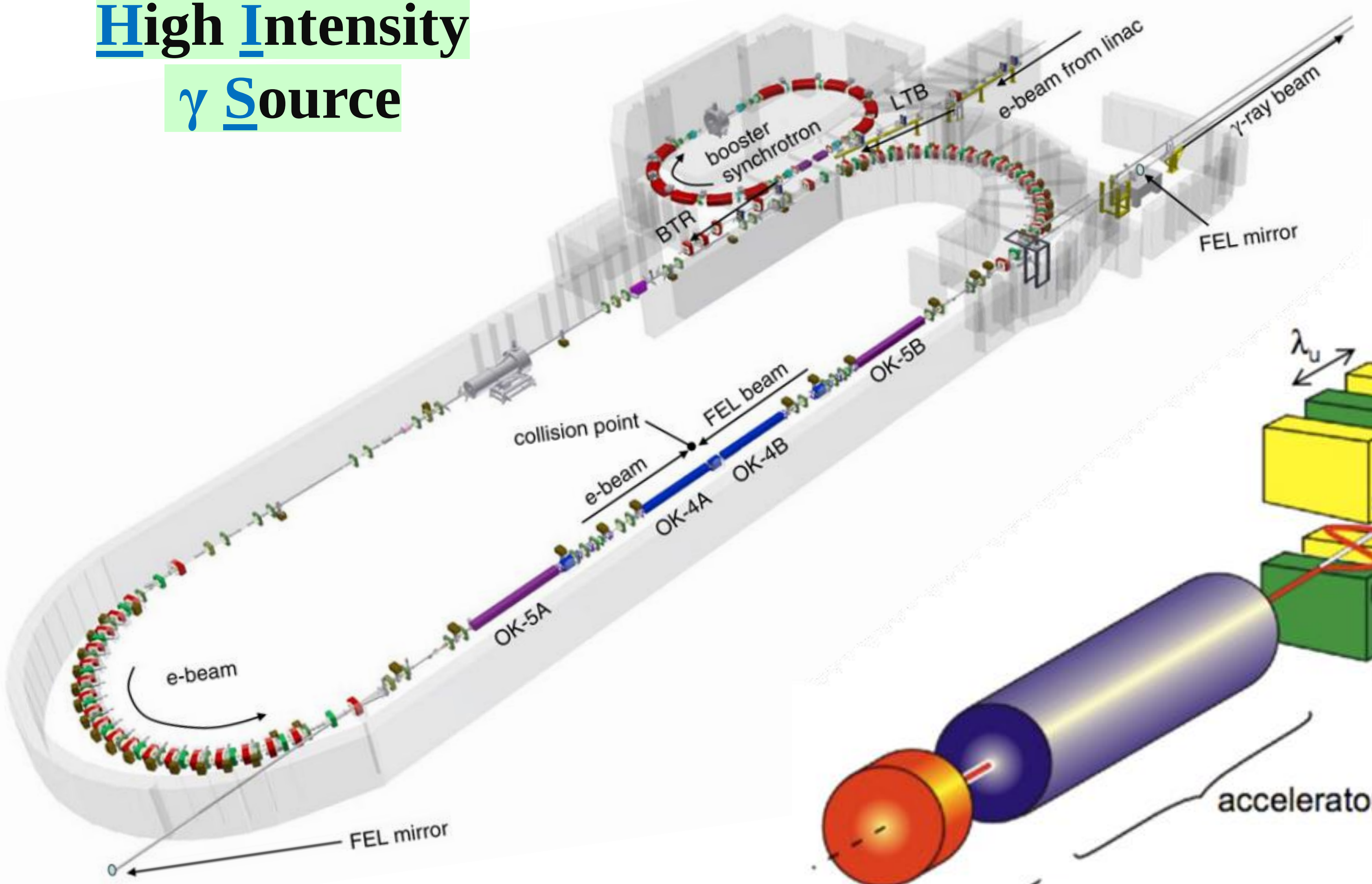
$\boldsymbol{{}^{7}Li(\gamma,t)\,{}^{4}He}$ ➡ Inverse reaction

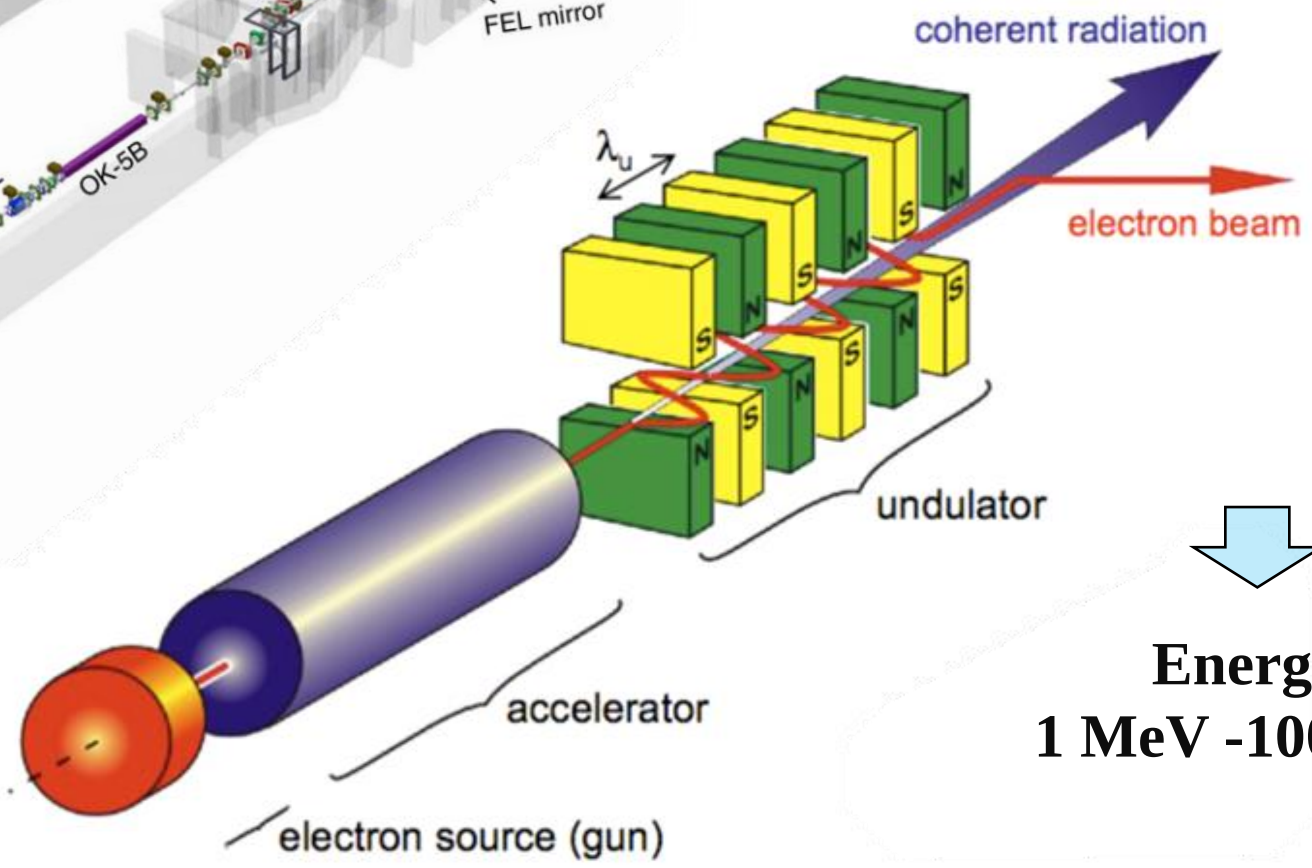
Lithium photodisintegration: k >100



Set-up at HIγS

High Intensity
γ Source

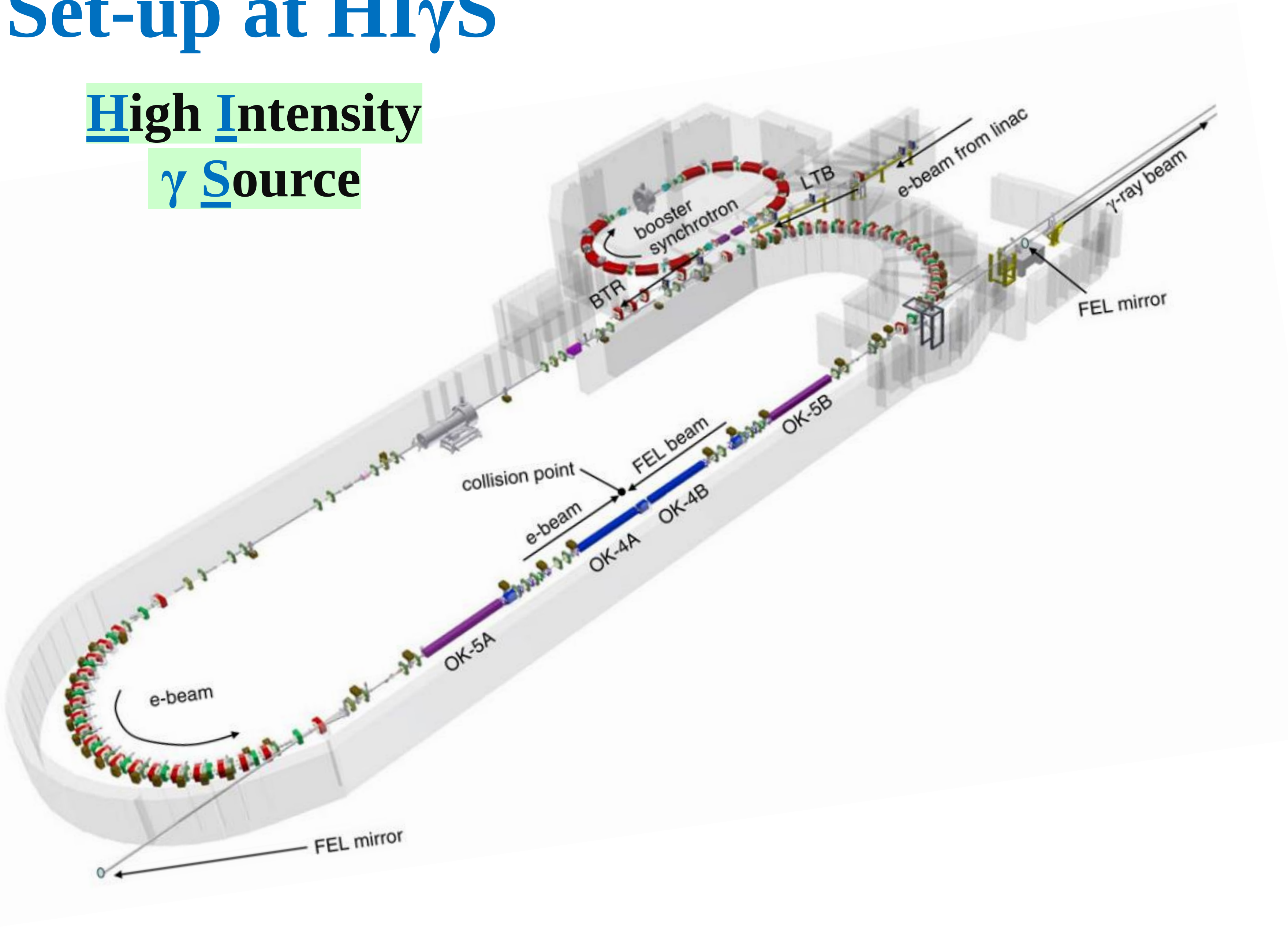


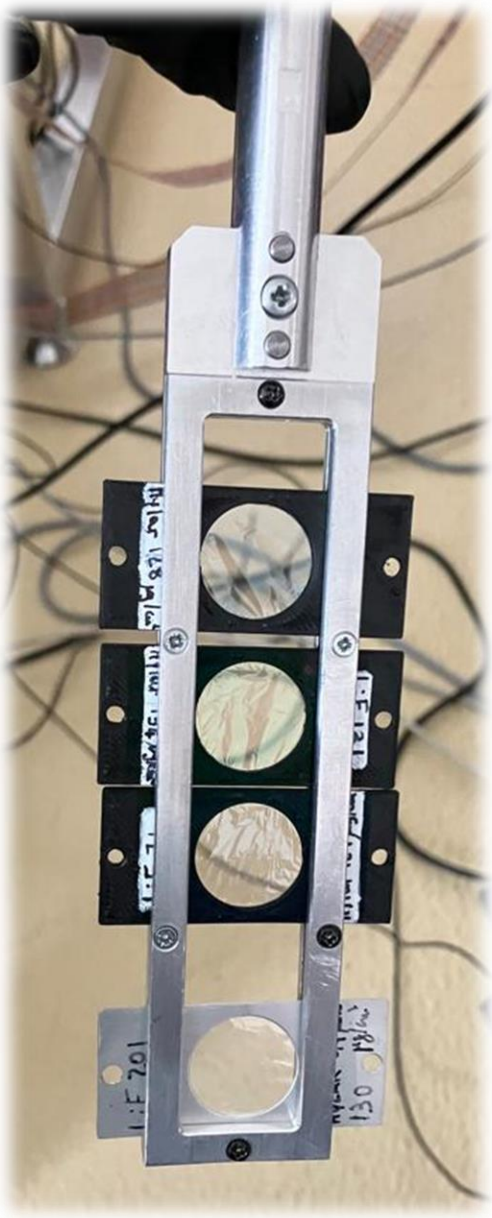


Energy:
1 MeV -100 MeV

Set-up at HIγS

High Intensity
γ Source





LiF/Mylar

Set-up at HIγS

High Intensity
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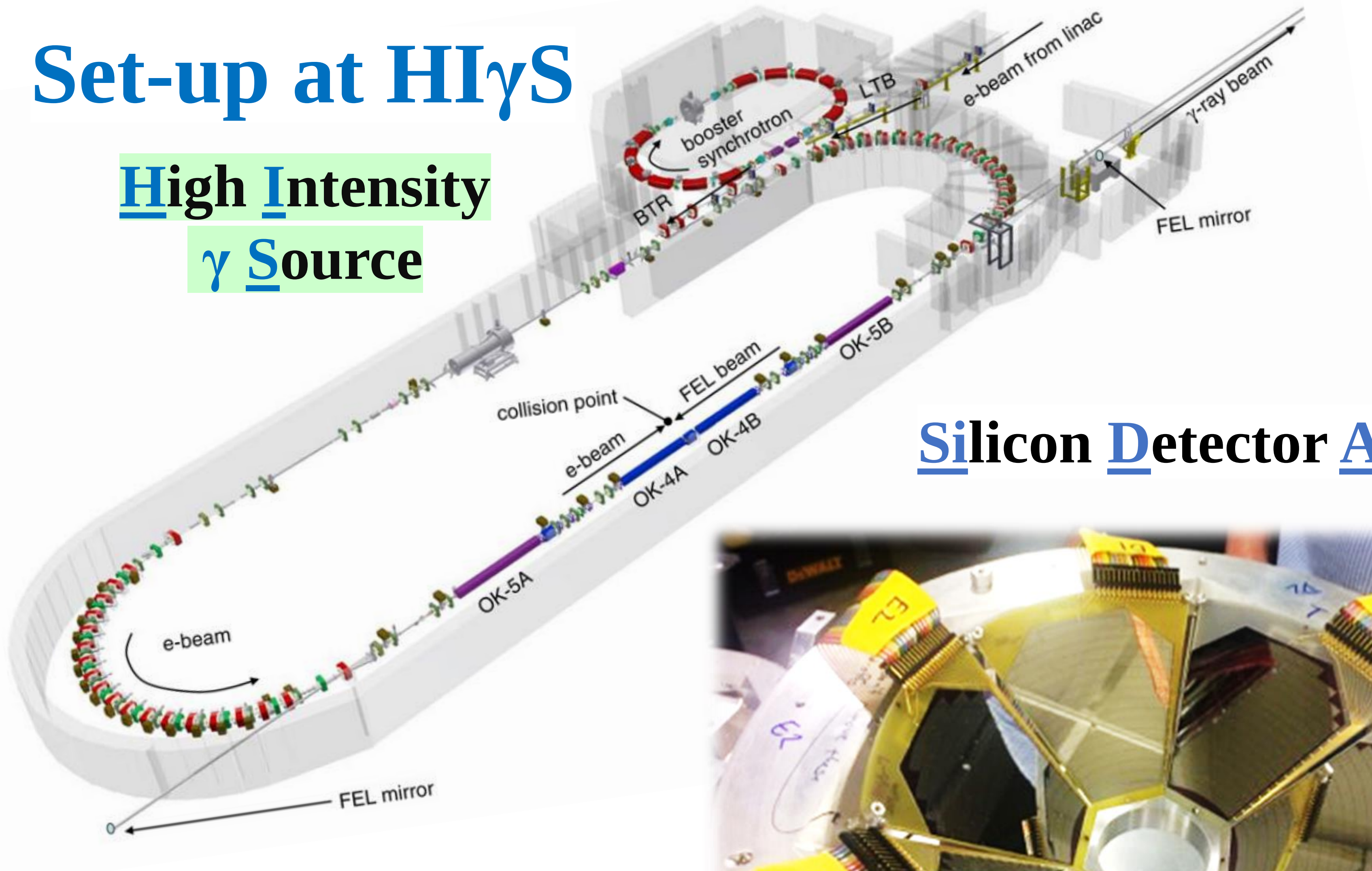
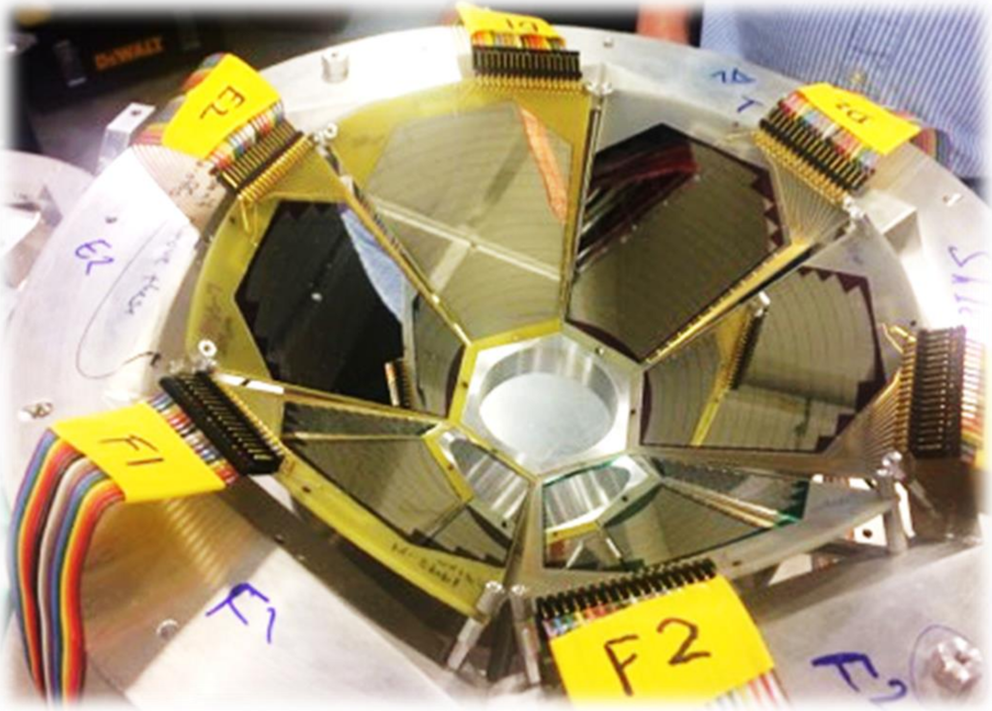
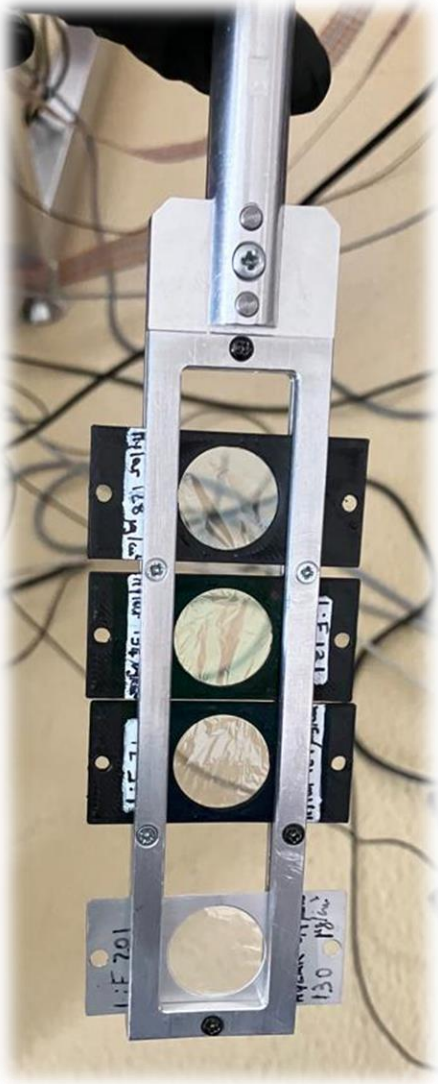


Silicon Detector Array





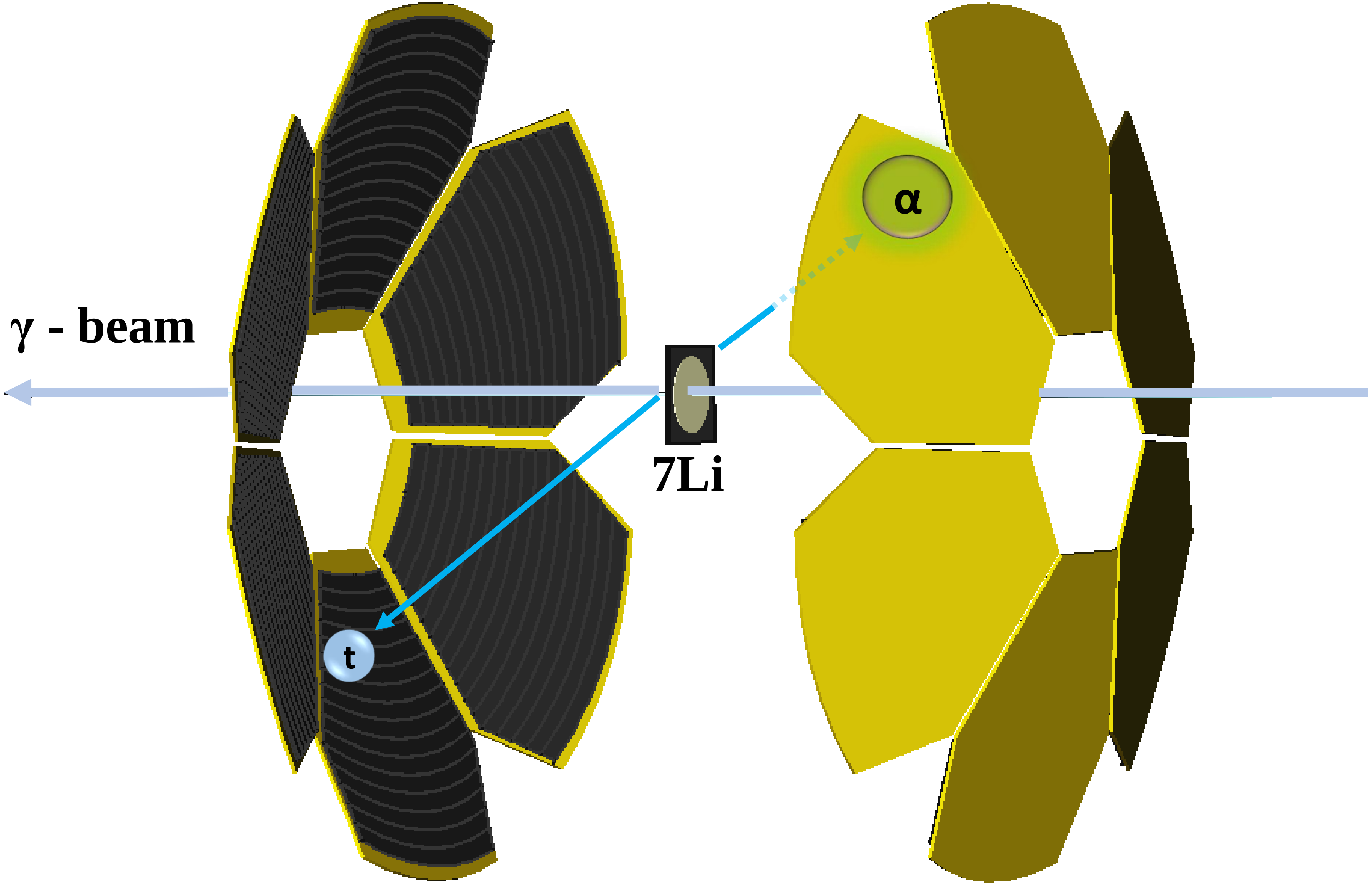
LiF/Mylar

SIDAR

Silicon
Detector
Array

2 x 6 YY1
(16 strips)

192 channels



SIDAR

Silicon
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2 x 6 YY1
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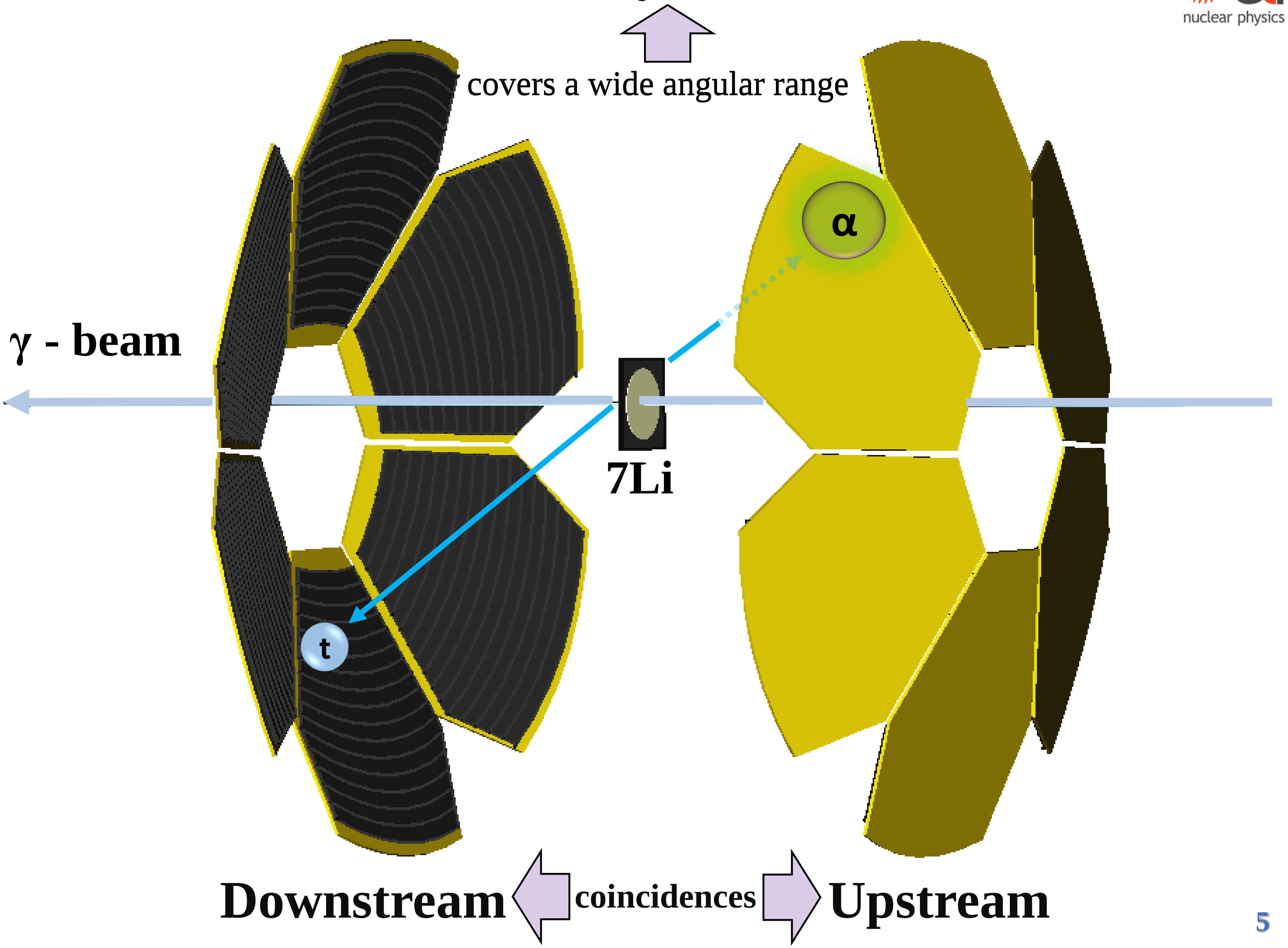
192 channels

Efficiency ~ 38.66%



The old experiment:
2017
4.4 MeV - 10 MeV

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

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

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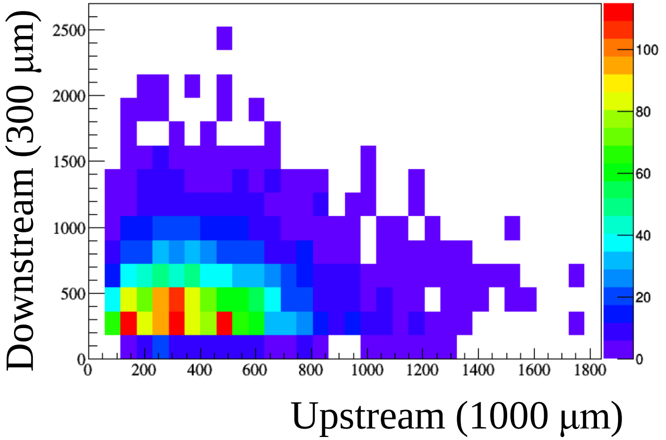

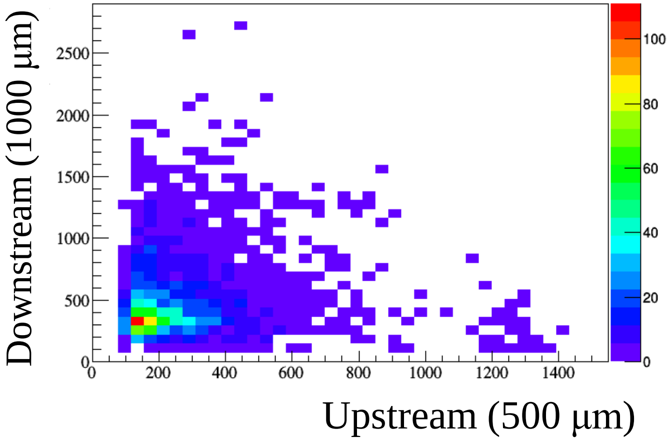

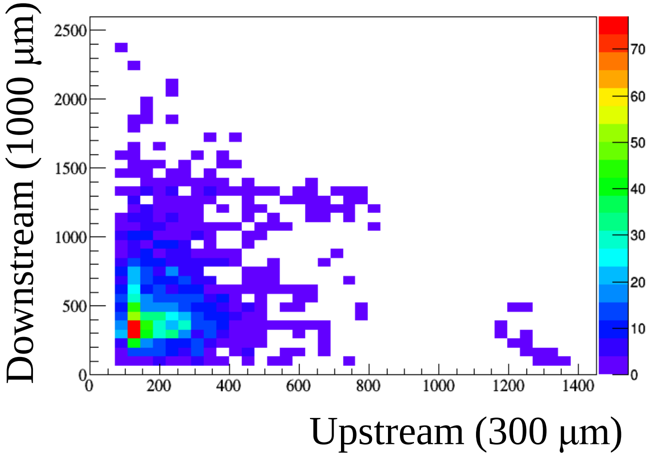

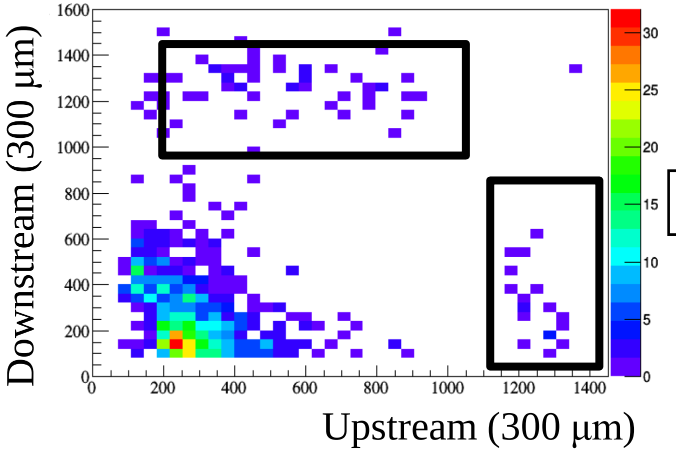

Coincidences corresponding to 4.4 MeV gamma beam were observed only in the thinner detectors

The old experiment:

2017

4.4 MeV - 10 MeV

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

The new experiment:

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IMPROVEMENTS

1. **Array of thinner Si detectors: 100 (d) &65 (u) μm**
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)**

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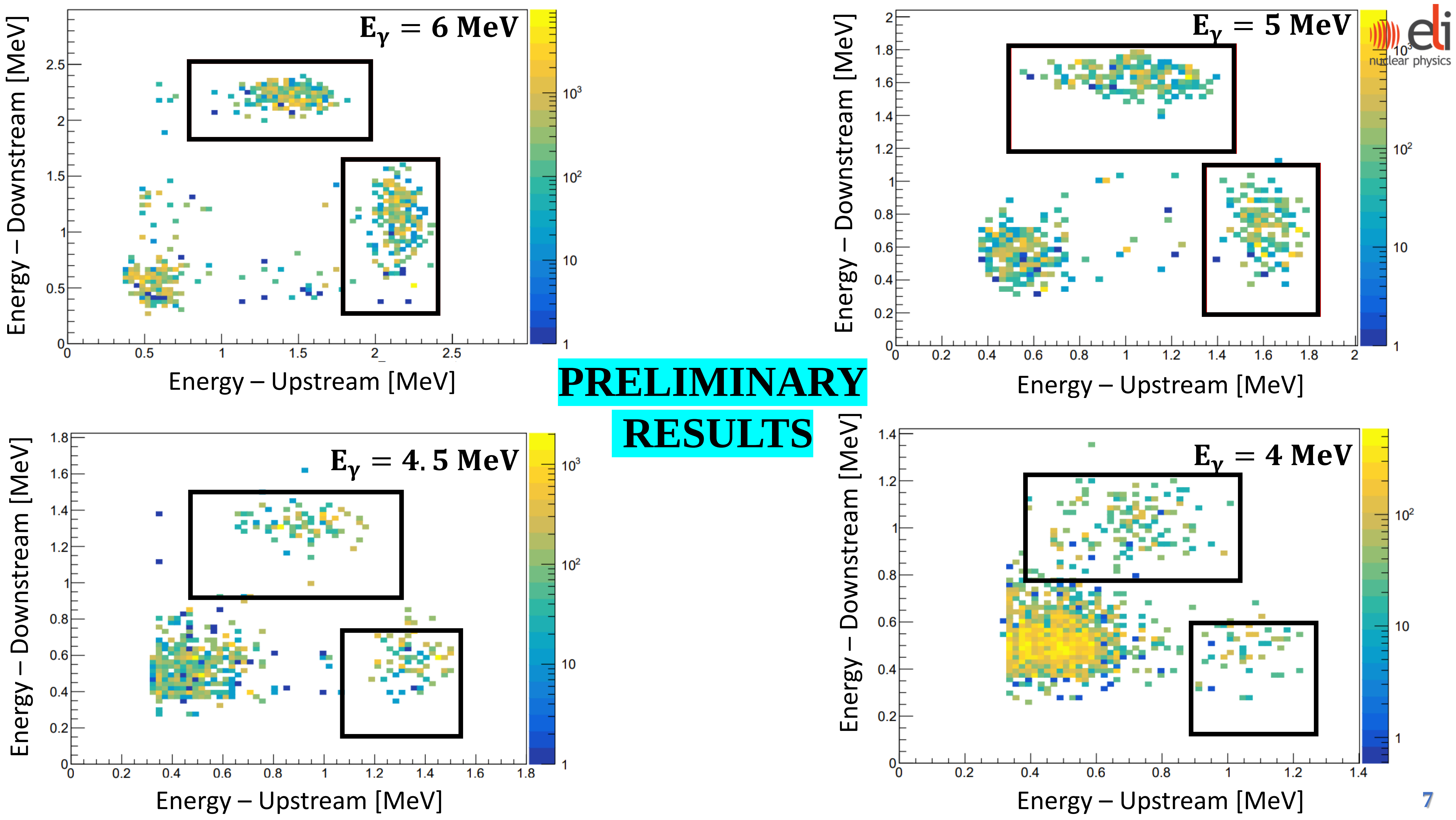
The coincidences have been clearly separated even for the lowest energy

The background has been highly reduced



PRELIMINARY RESULTS

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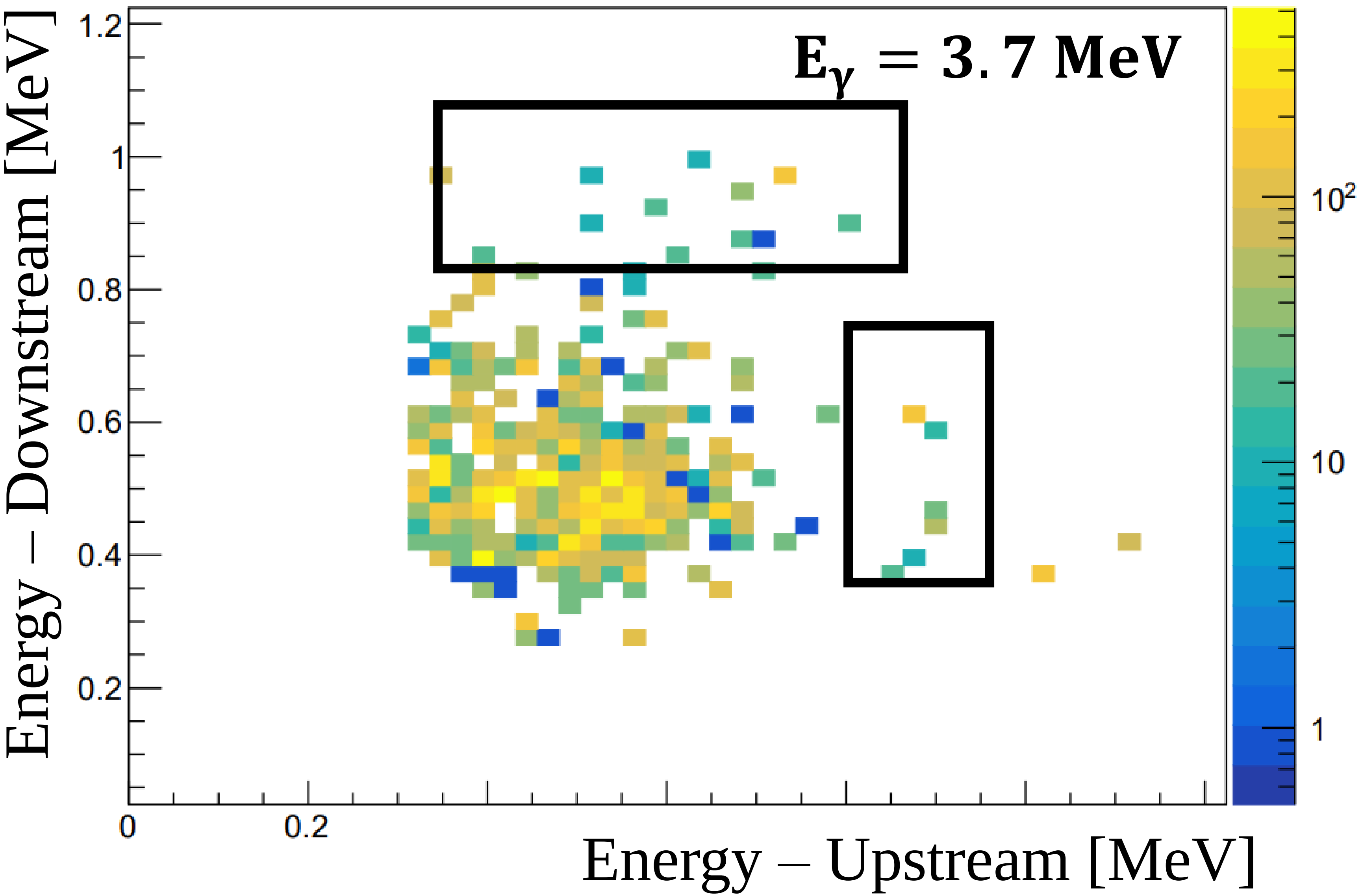

The ground state cross-section of the inverse $^{7}Li(\gamma,\alpha)\,^{3}H$ reaction

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%

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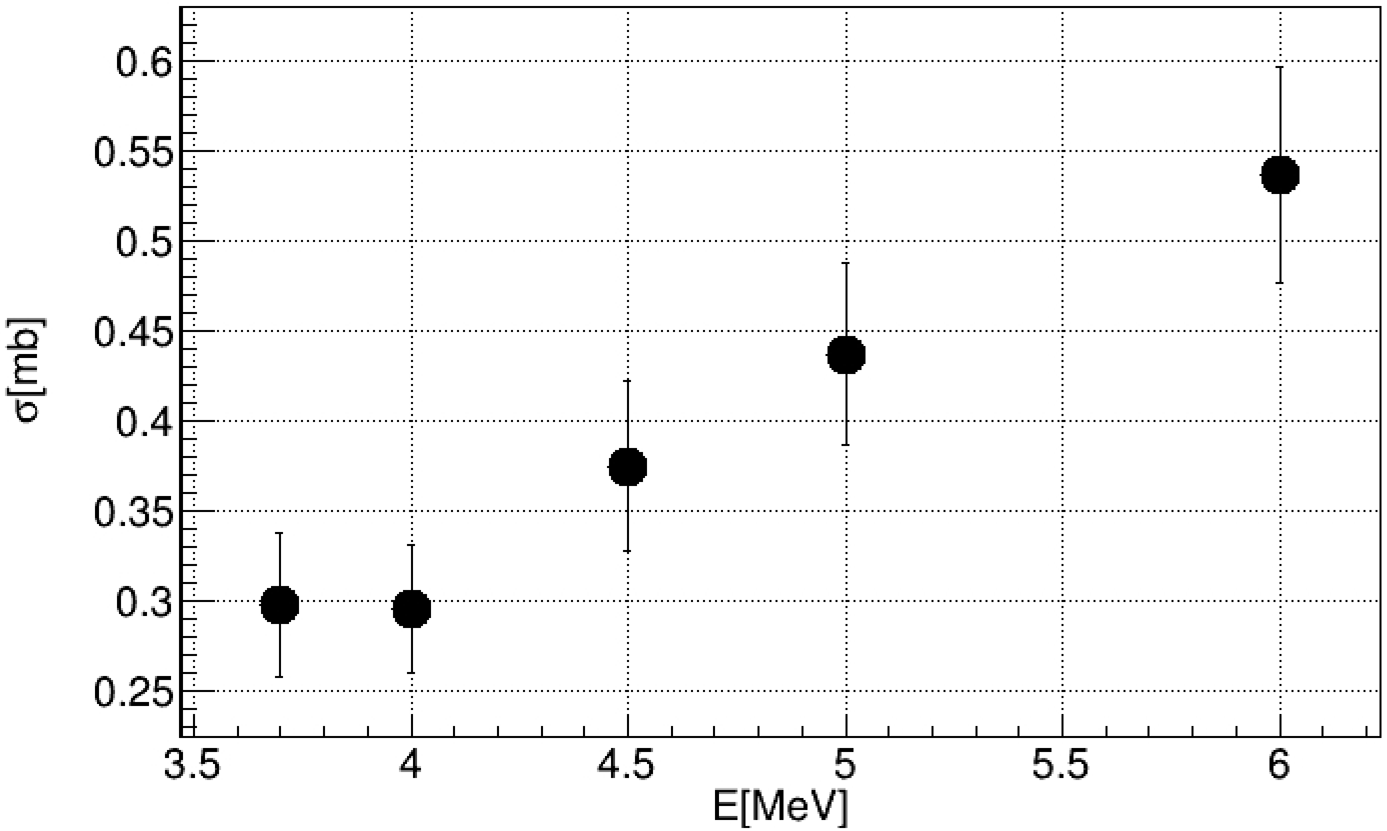
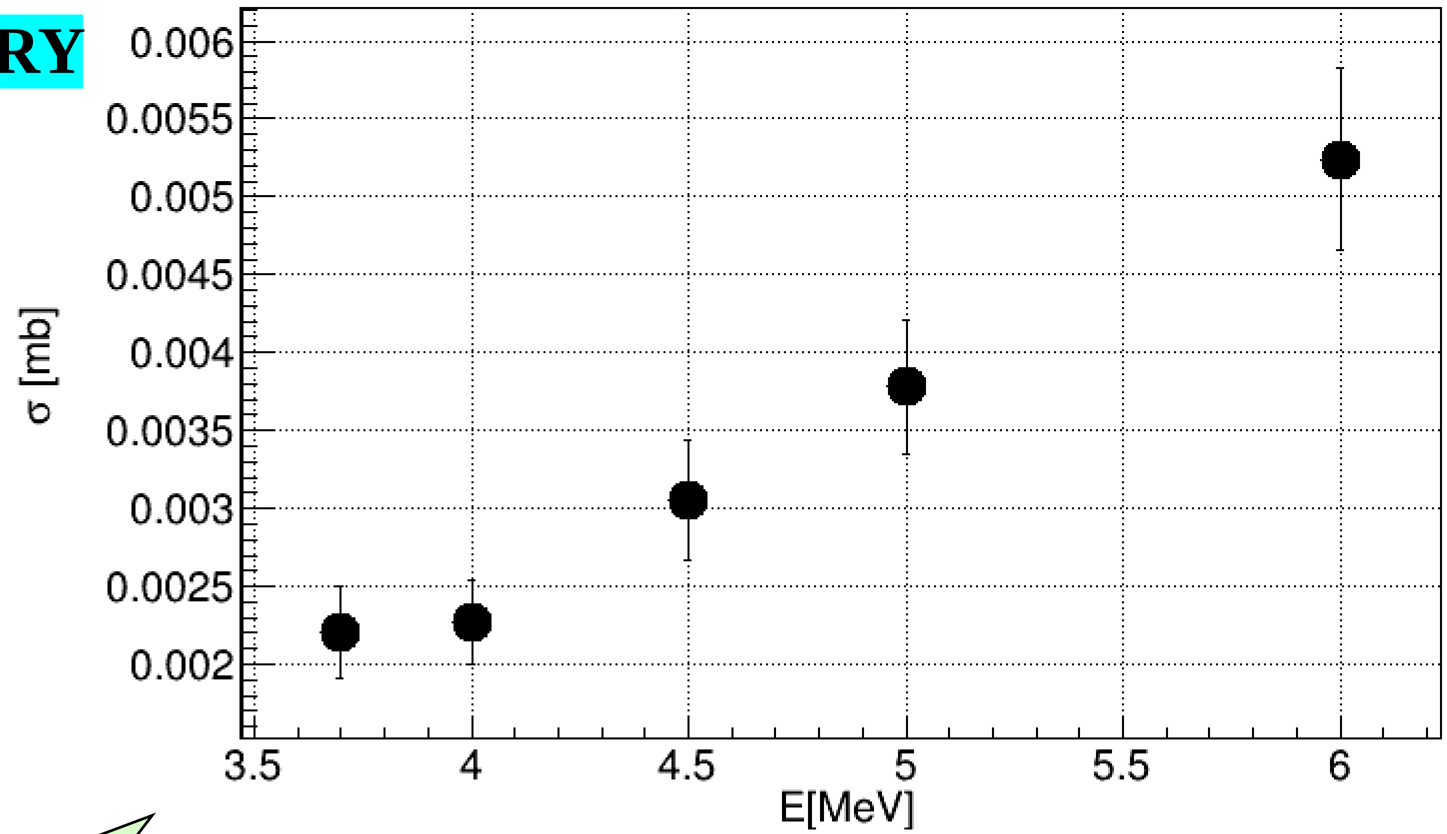


Quantity	Uncertainty
Events no	~ 5-18 %
Intensity	~ 10%
Li-7 atoms no	~ 1%
Efficiency	~ 1%

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

PRELIMINARY RESULTS



PRELIMINARY RESULTS

Ground state : $j = s$

Photons: $2j+1=2$

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

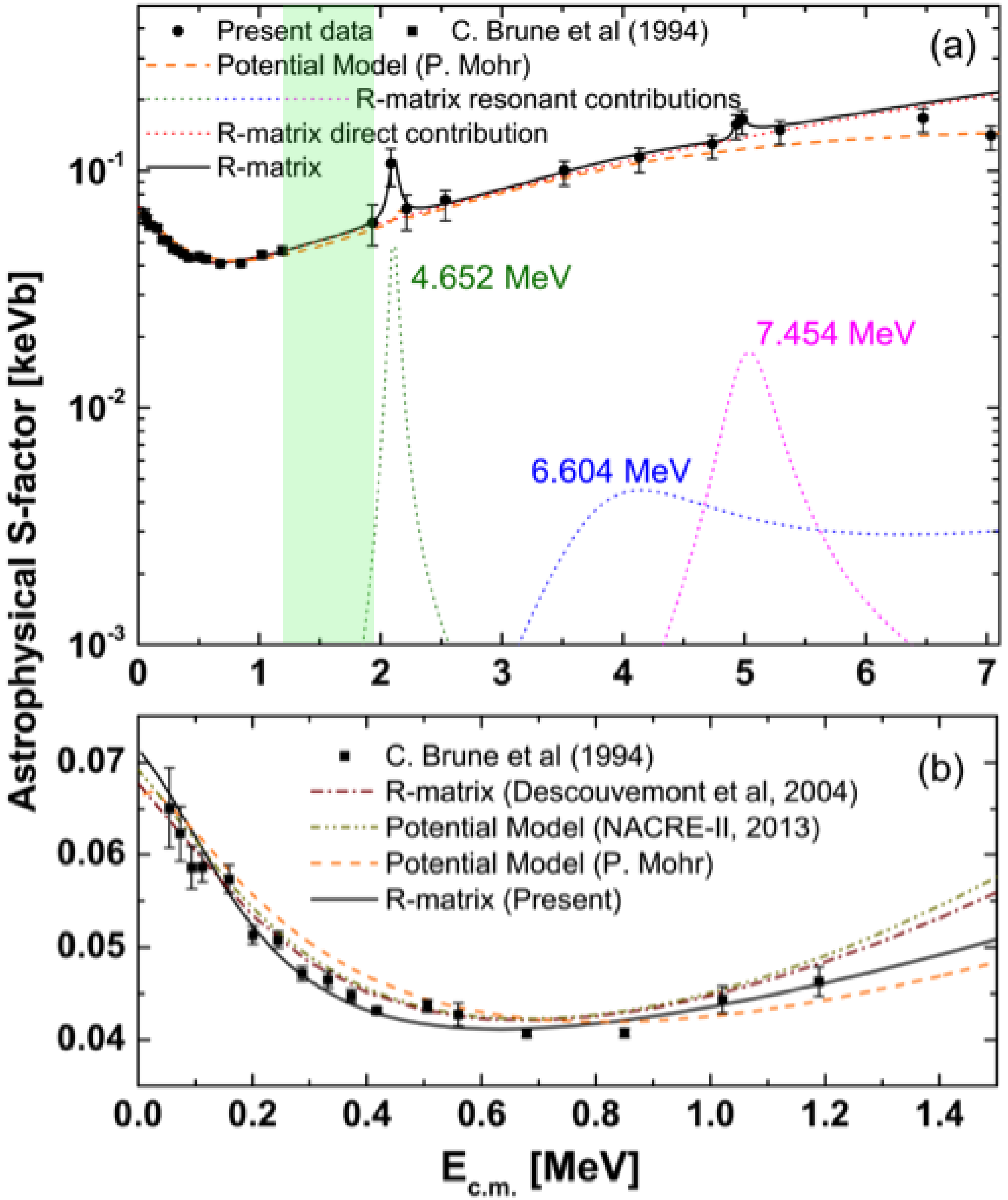
$Q_{\alpha t\to 7Li\gamma} = 1.397\ MeV$

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

Astrophysical S – factor

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

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



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Measurement of the $^{7}Li(\gamma,t)\,^{4}He$ 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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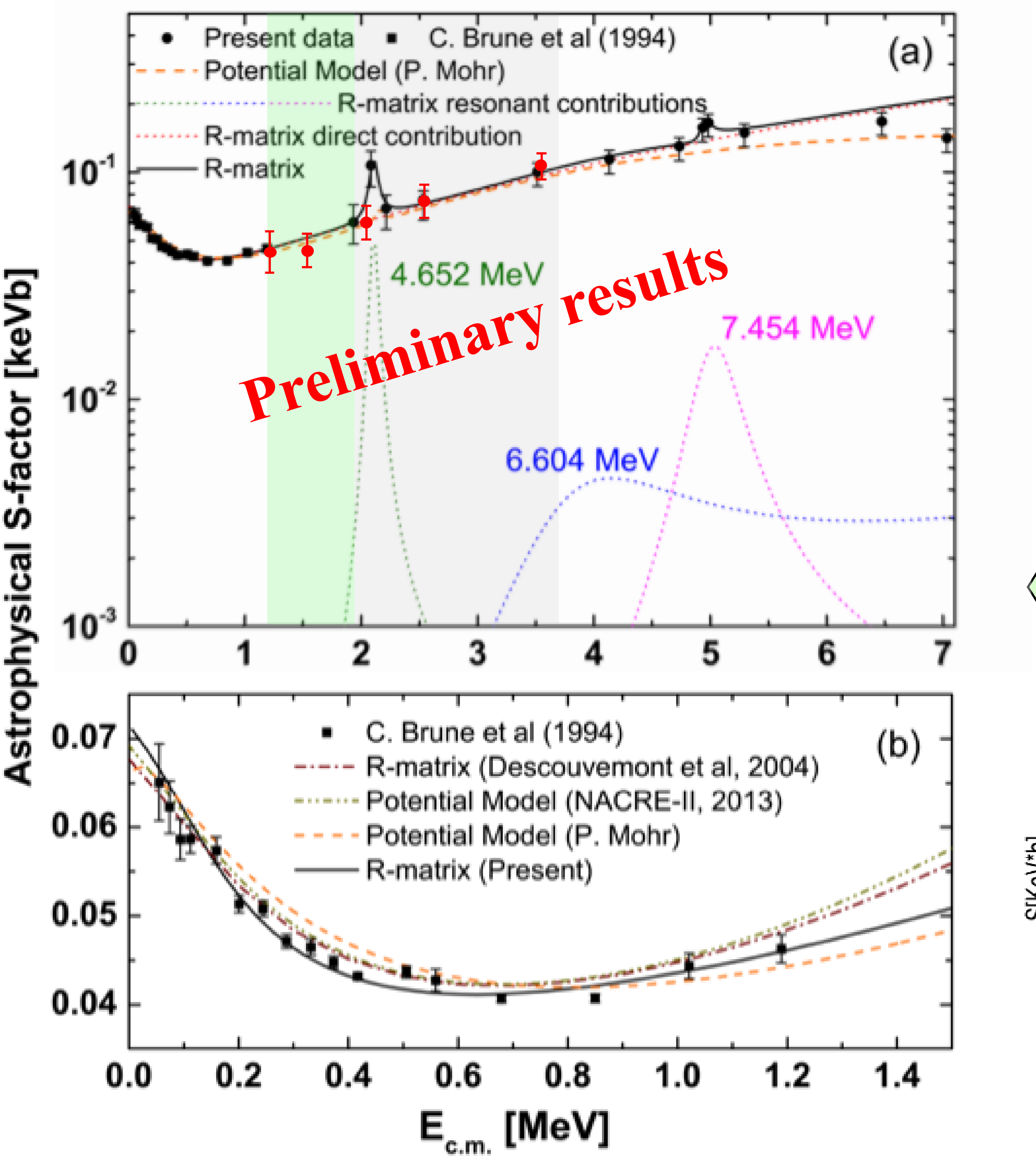

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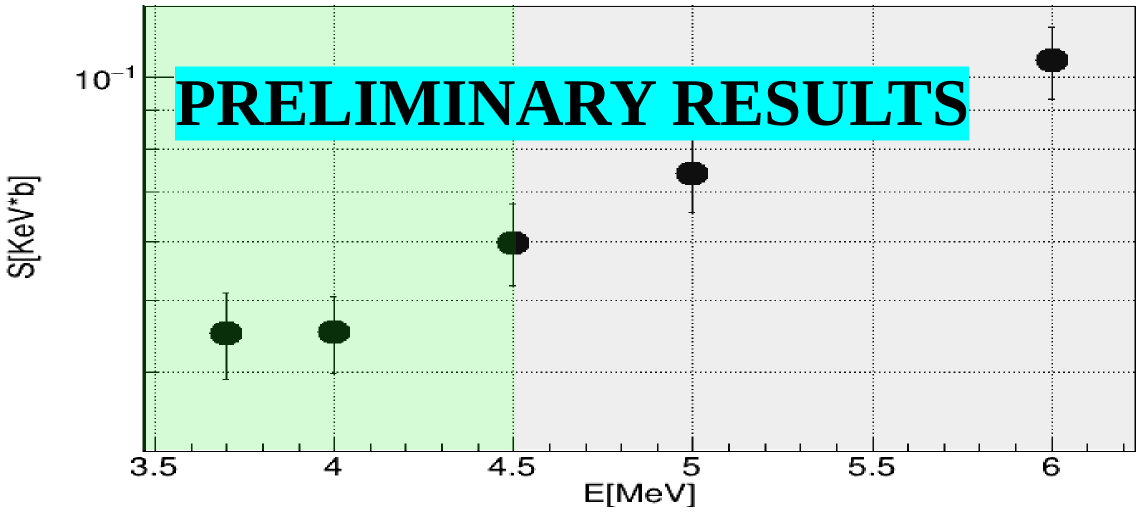

CONCLUSIONS…

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 inverse reaction has been studied in 2017 by our team at HIγS 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 with an improved set-up was performed in April 2023 to cover the gap between 3.7 and 6 MeV

In 2023 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 for attention!

- *Catalin Matei, D. Balabanski, <u>Ioana Kuncser</u>, <u>T. Petruse</u>, A. Pappalardo, H. Pai, Yi Xu (ELI-NP, Bucharest-Magurele, Romania)*
- *Steve Pain, Kelly Chipps, T. King, M Febbraro (ORNL – Oak Ridge, Tennessee, USA)*
- *M. Grinder, S. Balakrishnan, <u>Heather Garland</u>, 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)*
- *<u>O. Tindle</u>, <u>C. Haverson</u>, 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, <u>Gyoungmo GU</u> (Sungkyunkwan University, Suwon, Korea)*

Nuclear Physics in Astrophysics IX

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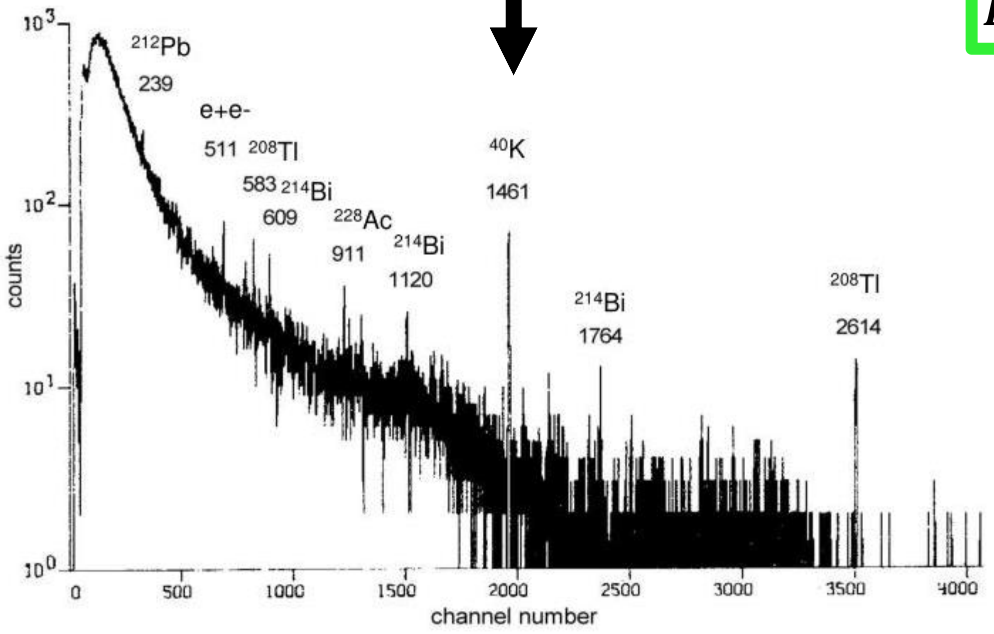
Gamma beam energy measurement

Ge DETECTOR + ATTENUATORS

Calibrated using background

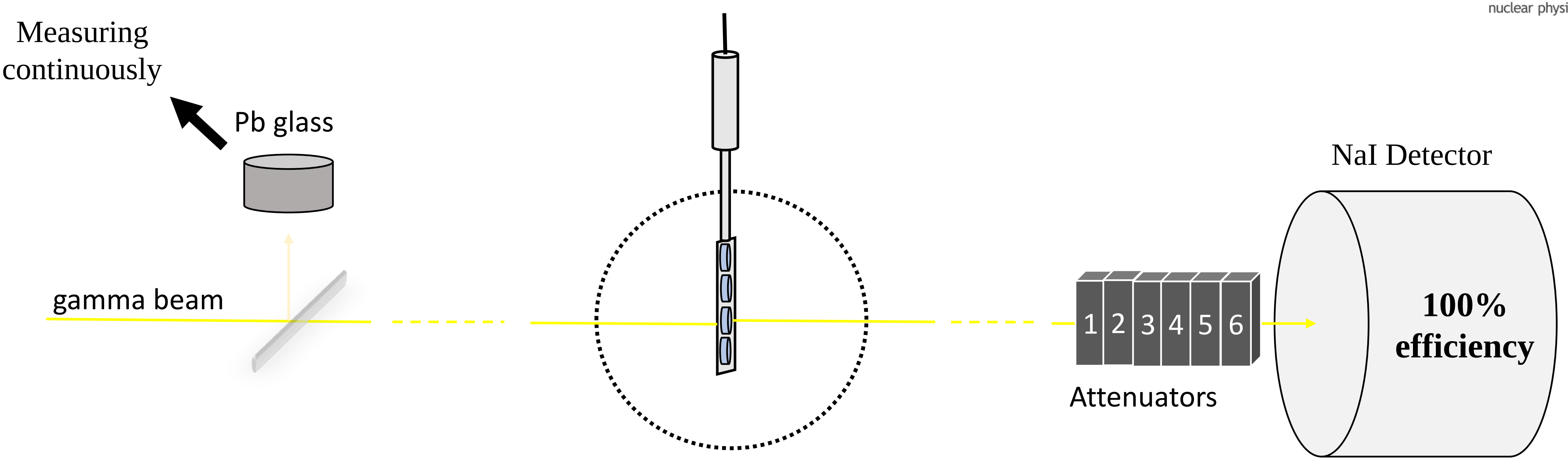
Known energy loss

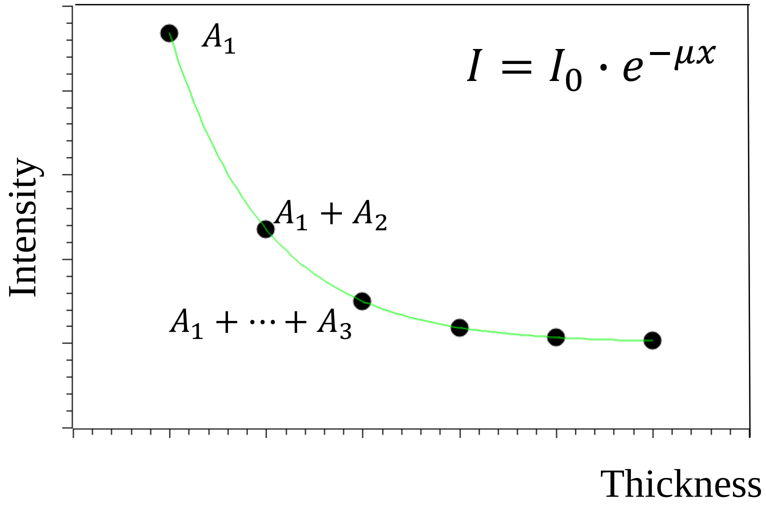
$$E_\gamma = E_{det} + E_{loss}$$

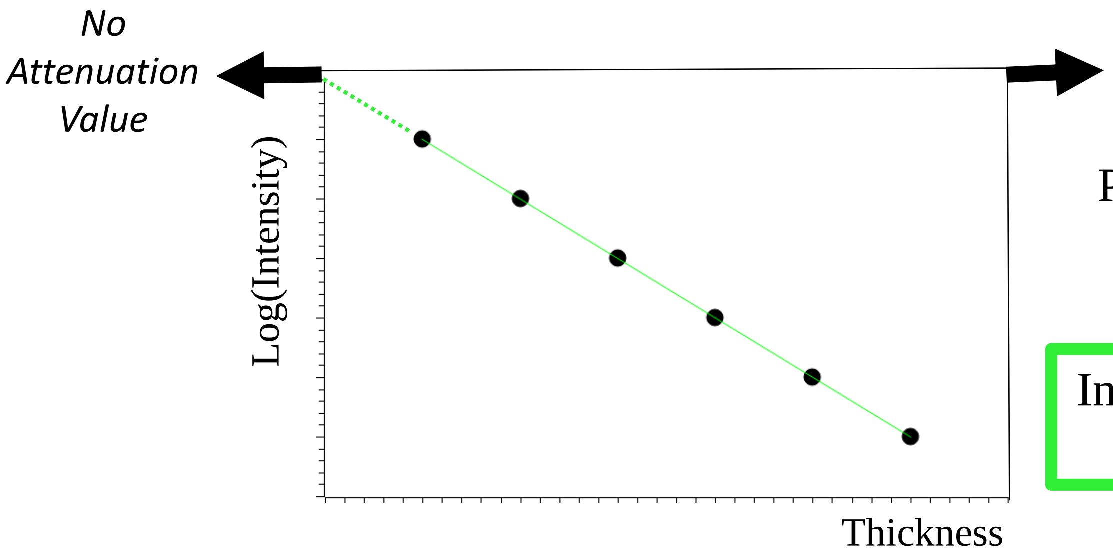


39.35 cm
of
copper

Gamma beam intensity measurement







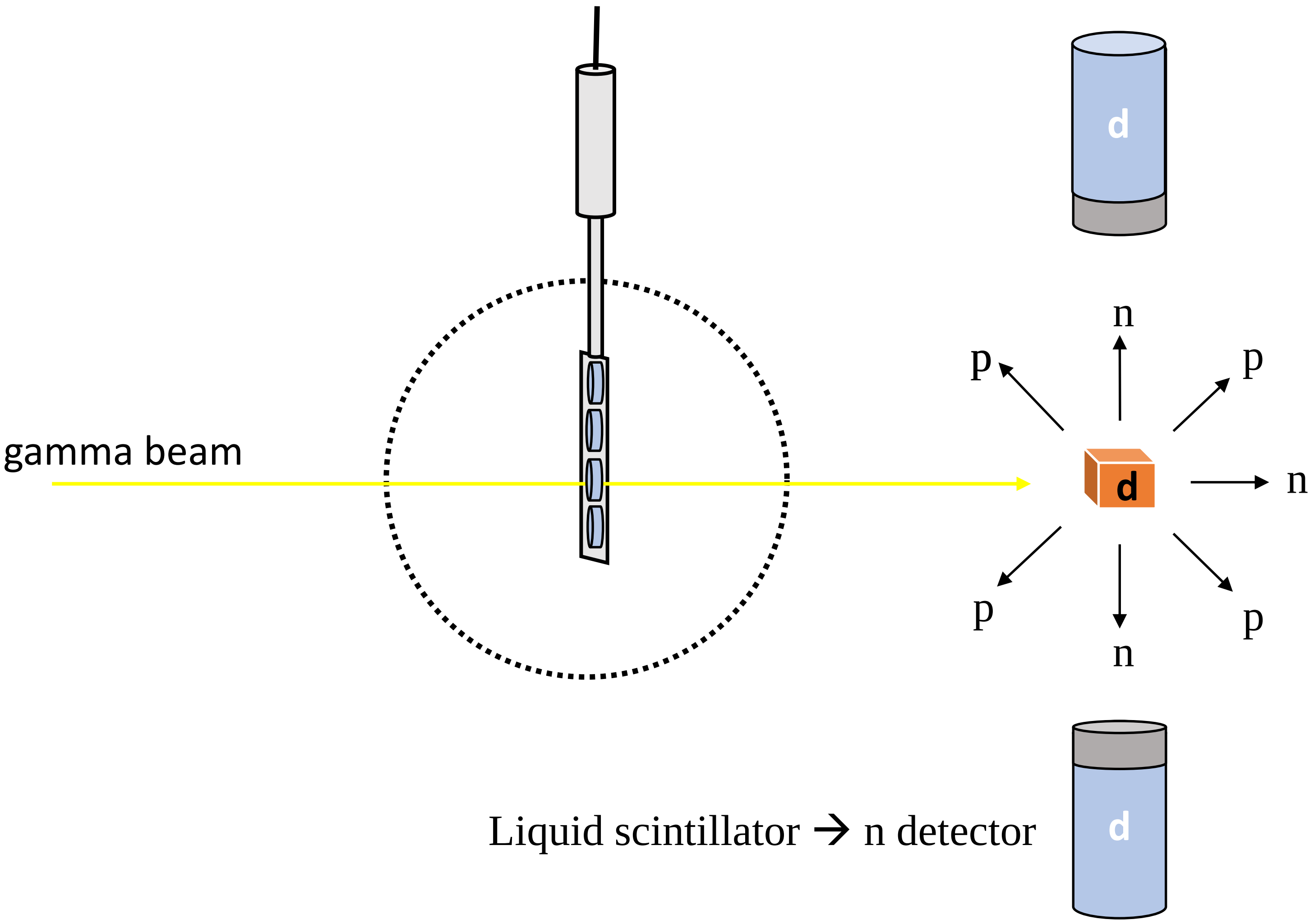
Coefficient related to the energy of the beam

Pb glass intensity calibration

↓

Intensity measurement during the run

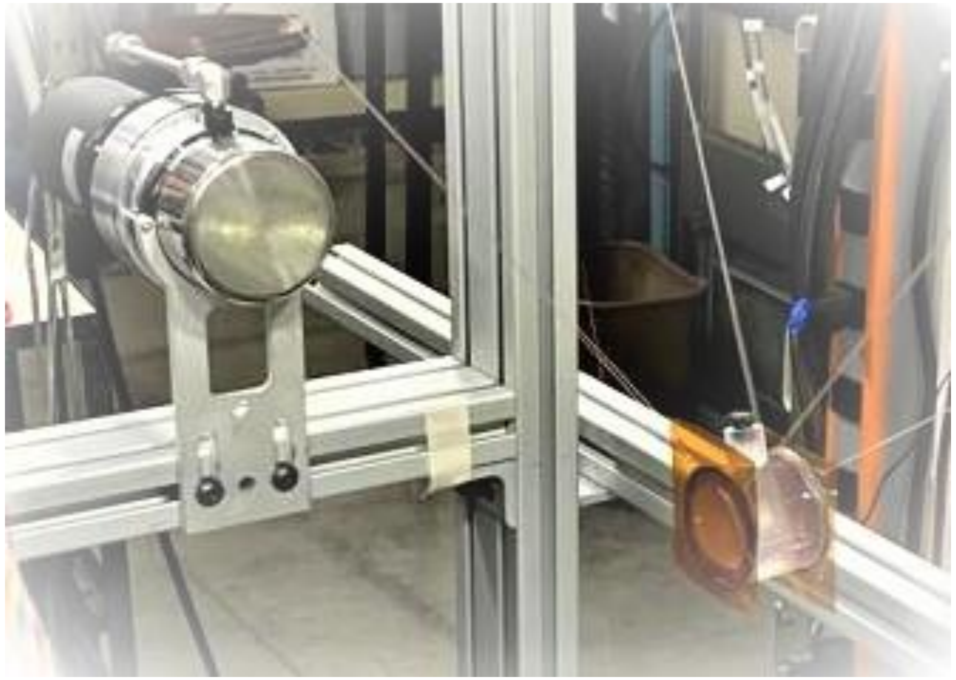
Gamma beam intensity measurement



Liquid scintillator → n detector

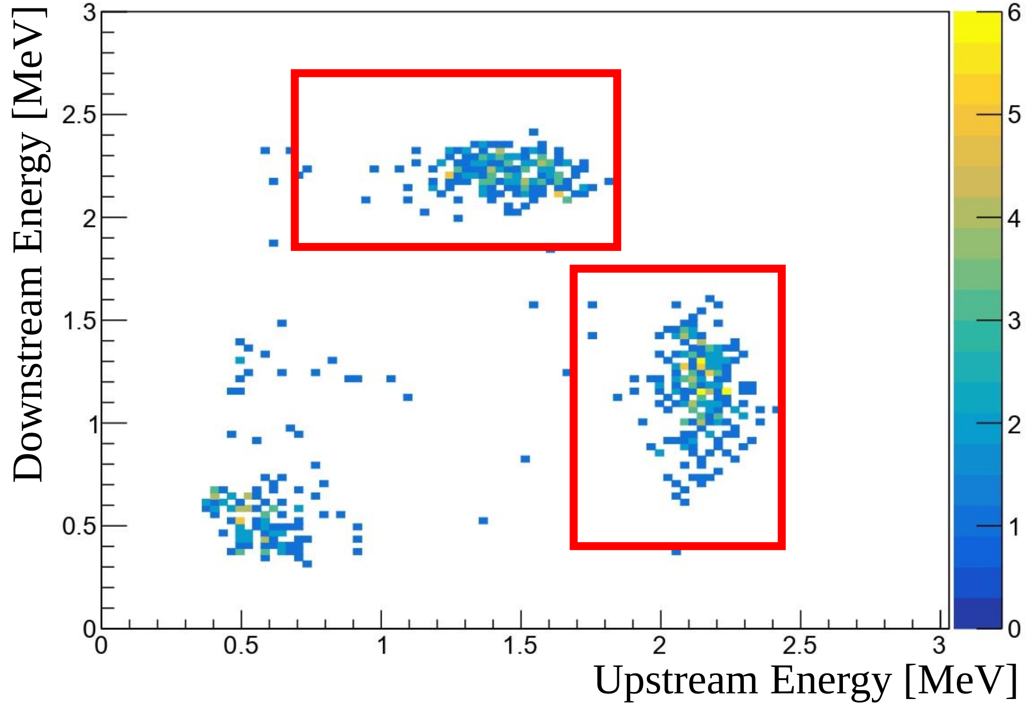
deuterium photodisintegration

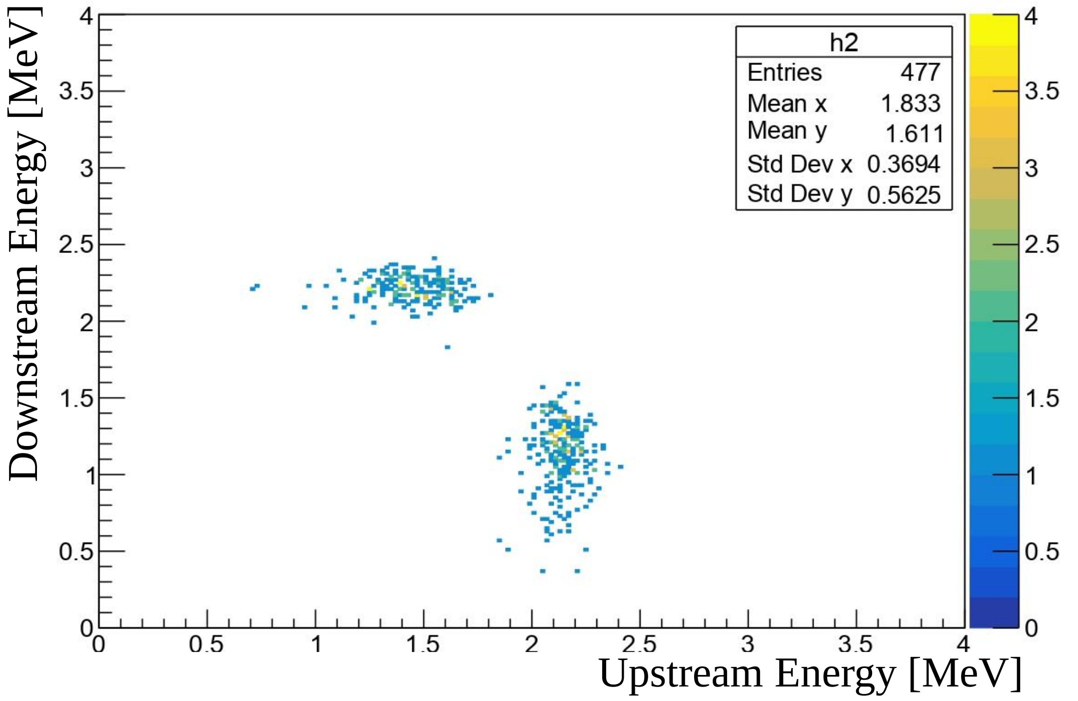
$$\boxed{d + \gamma = n + \mathrm{p} + 2.2\ \mathrm{MeV}}$$



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

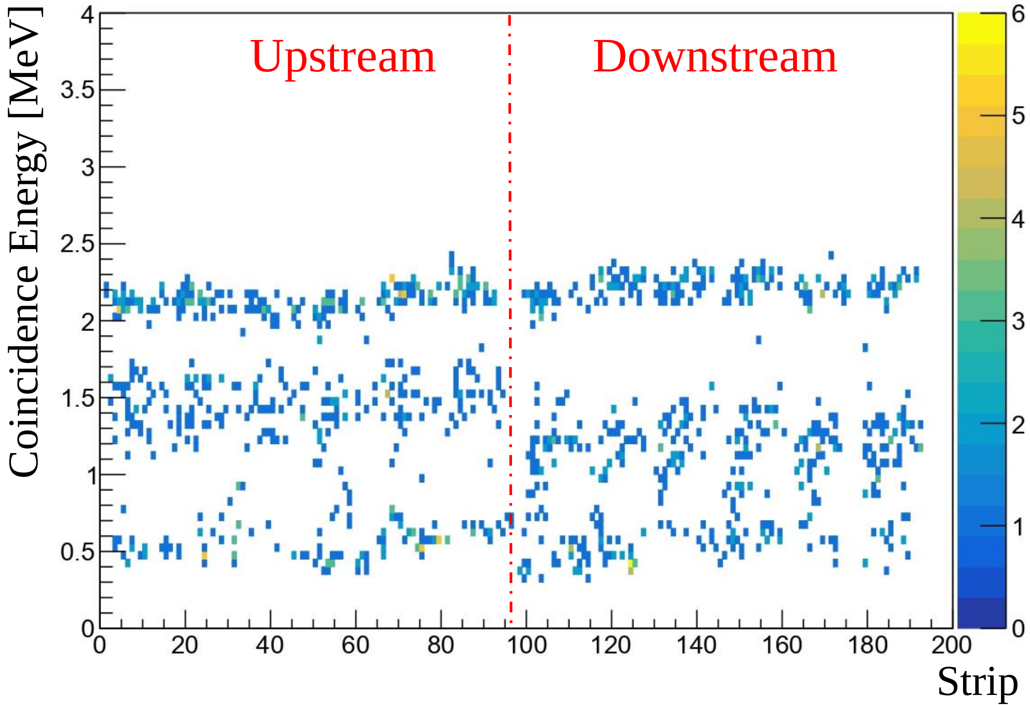
$$\boxed{\begin{array}{c} Nr\ of\ neutrons: \\ \varepsilon n = \sigma_{photodis} \cdot N_d \cdot I_\gamma \end{array}}$$

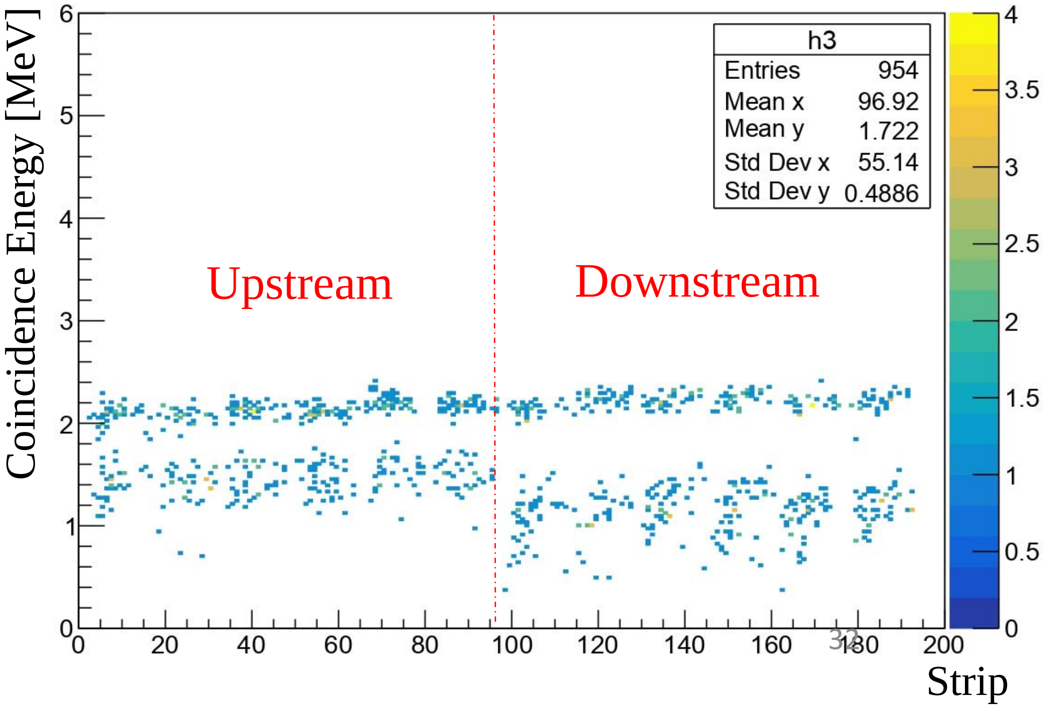


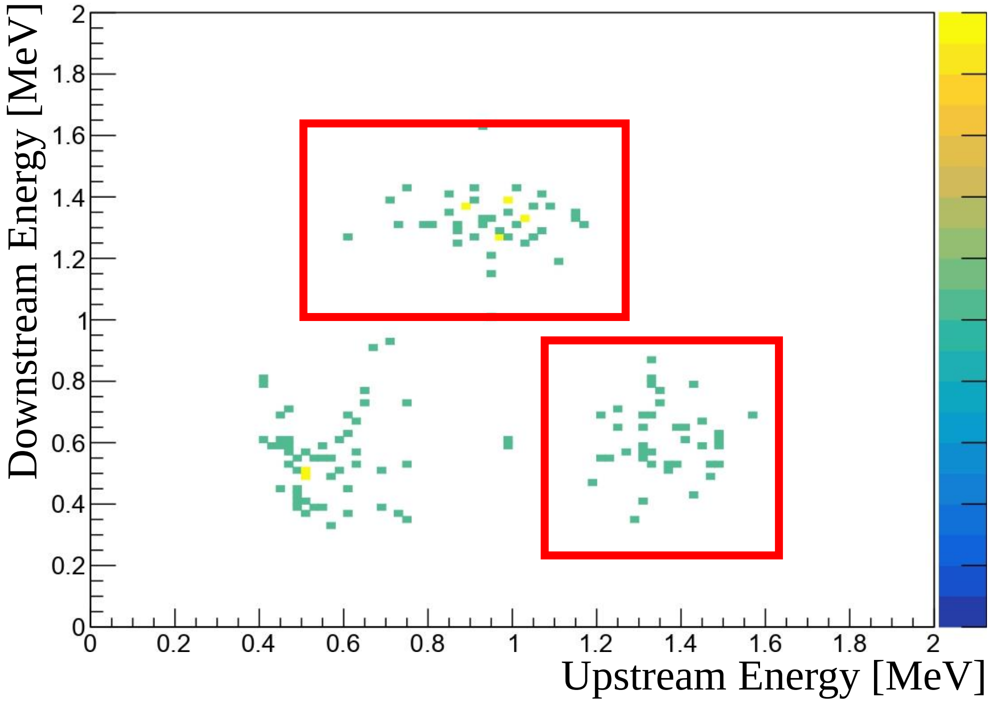


Background can be easily subtracted for

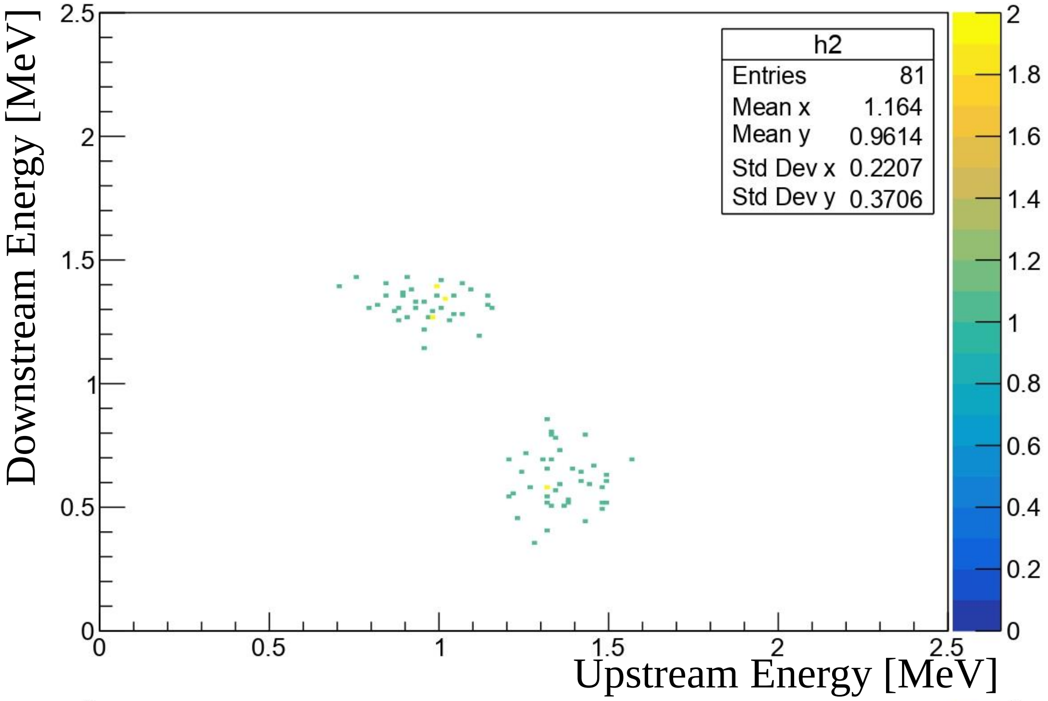
6 MeV

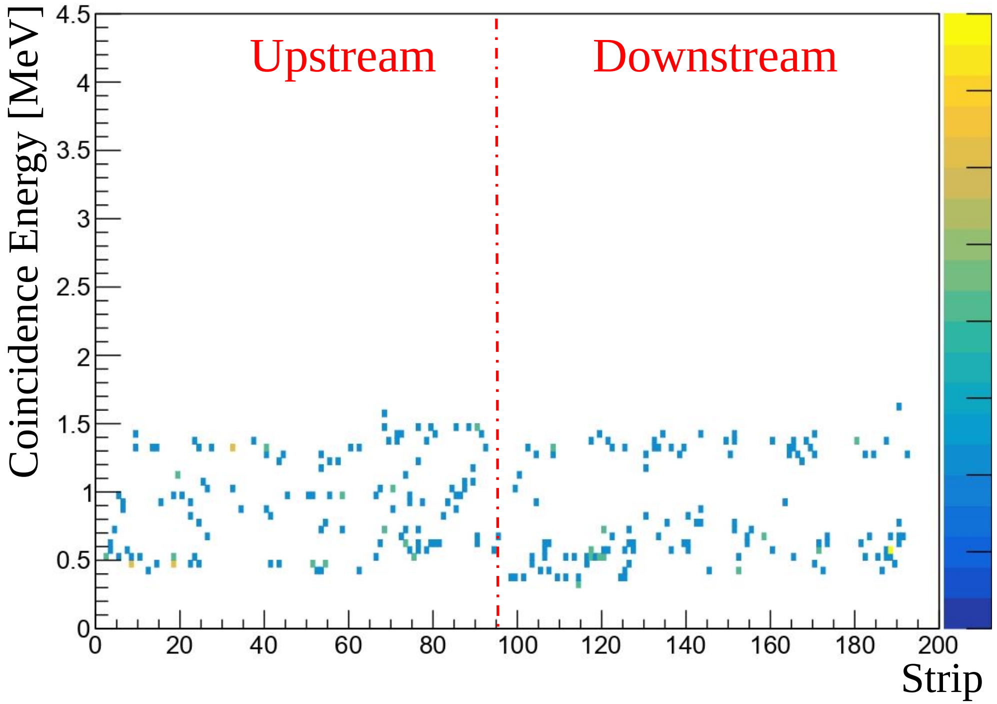


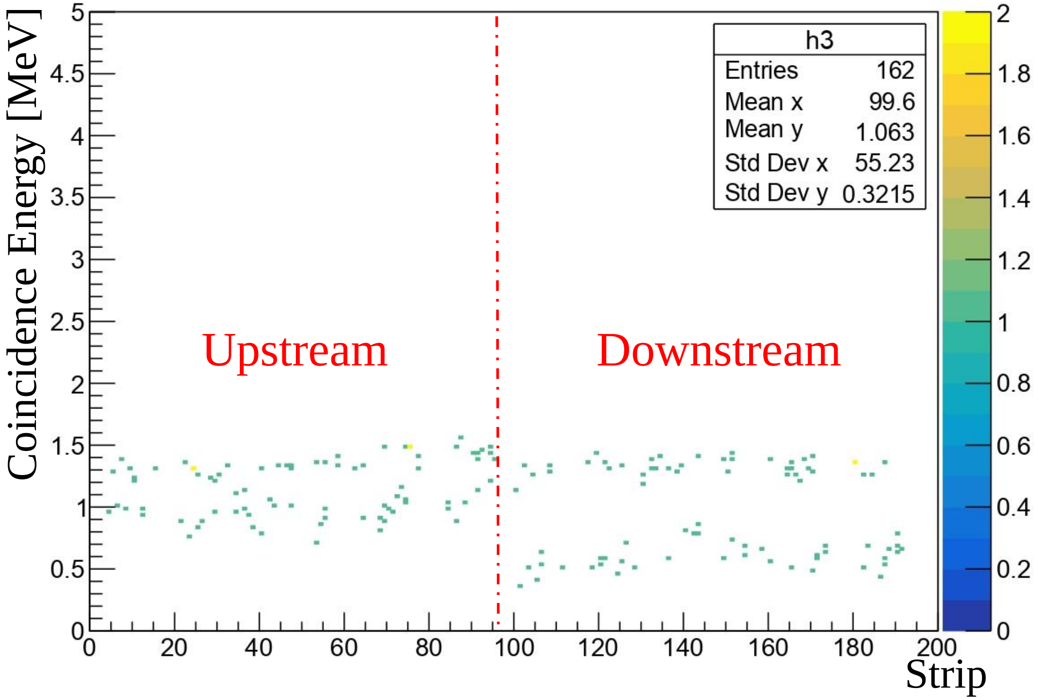


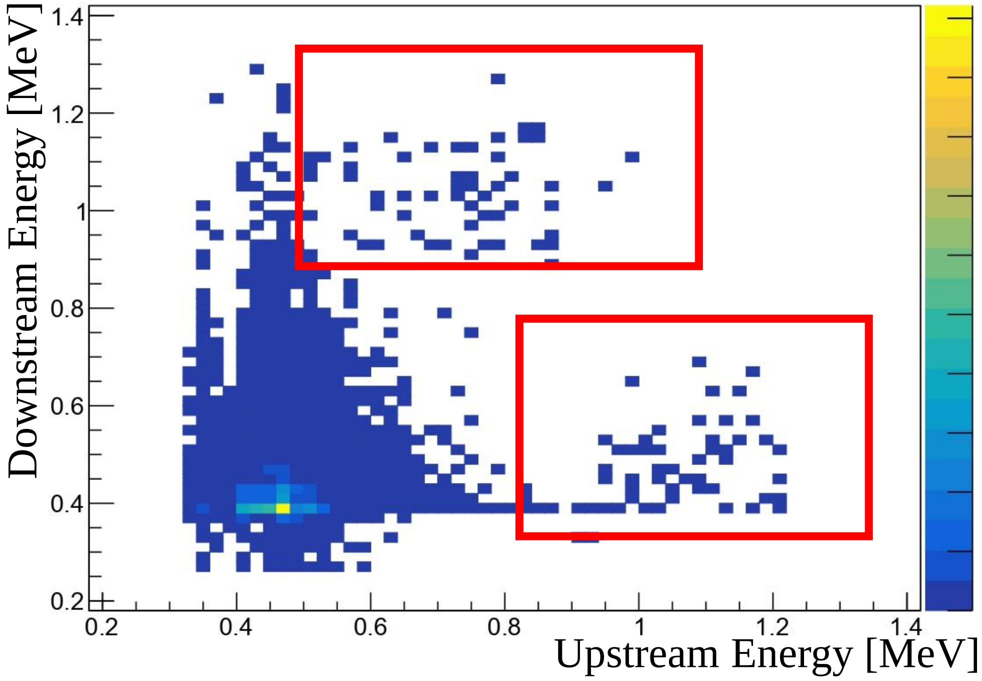


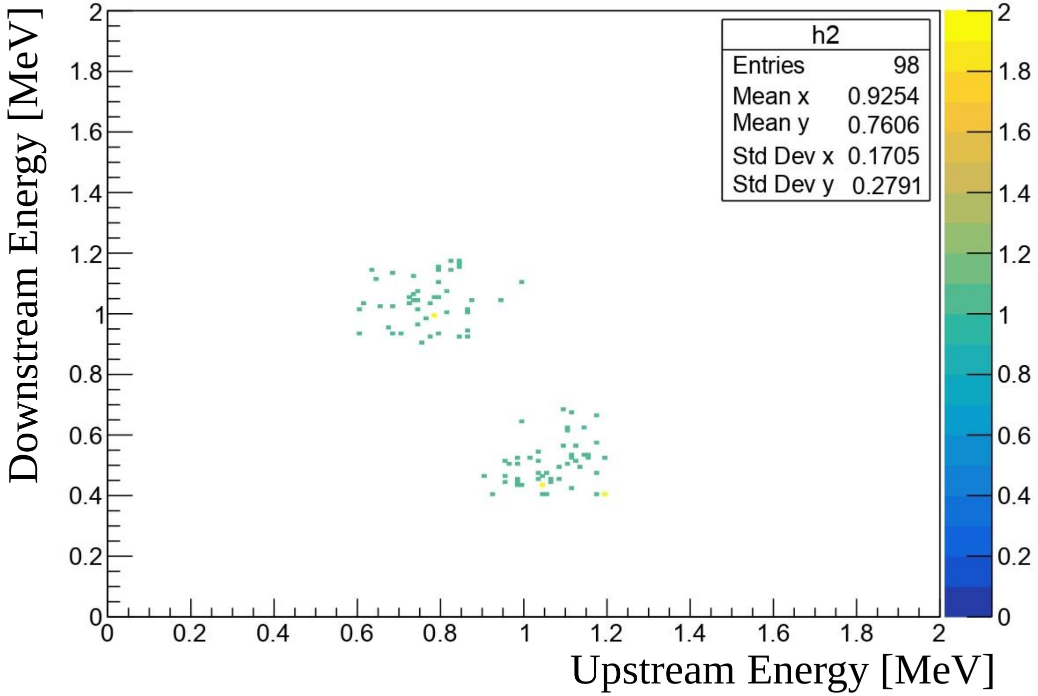
And even for **4.5 MeV**



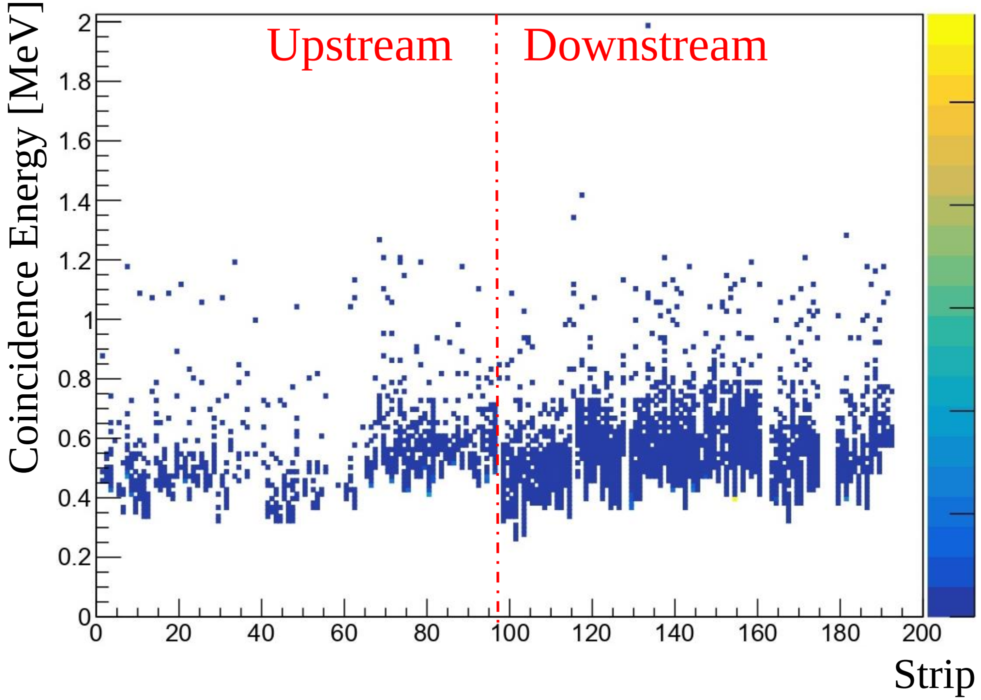


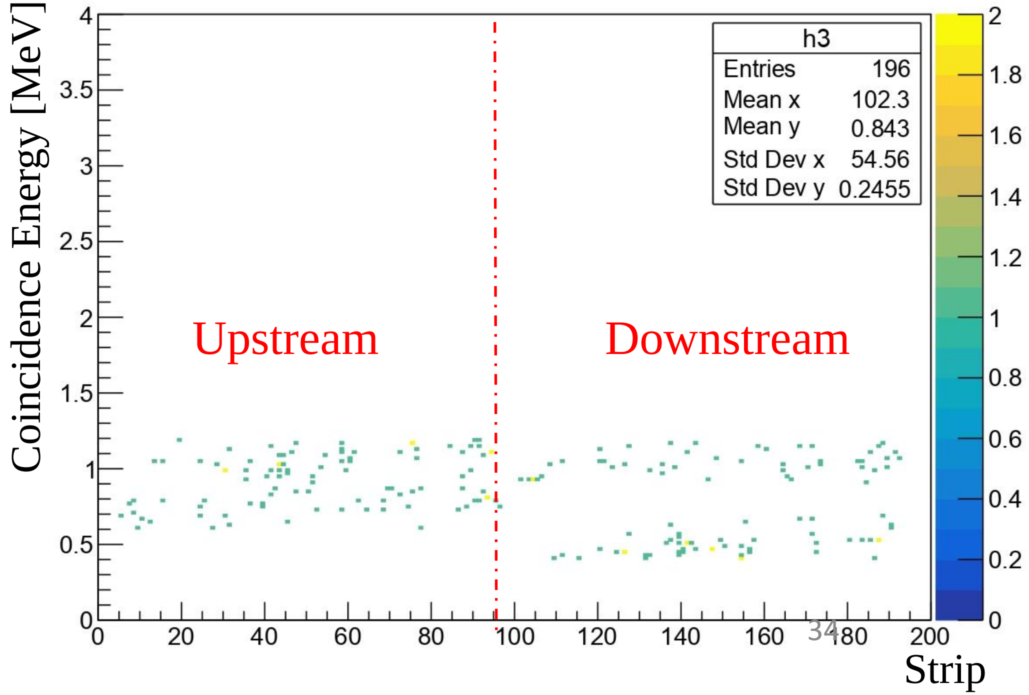


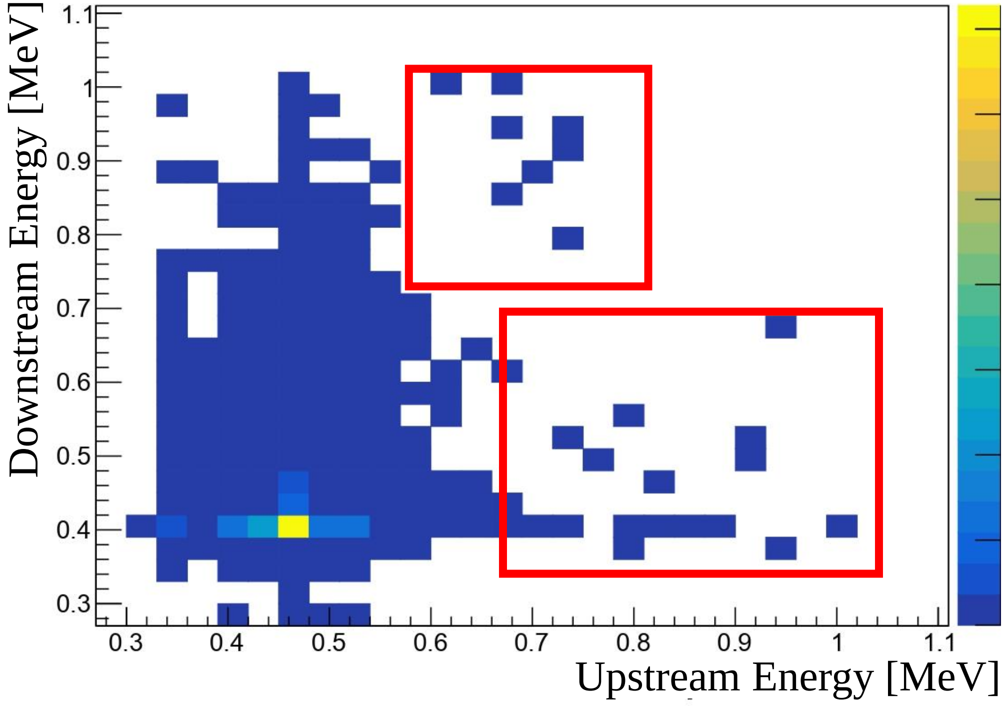


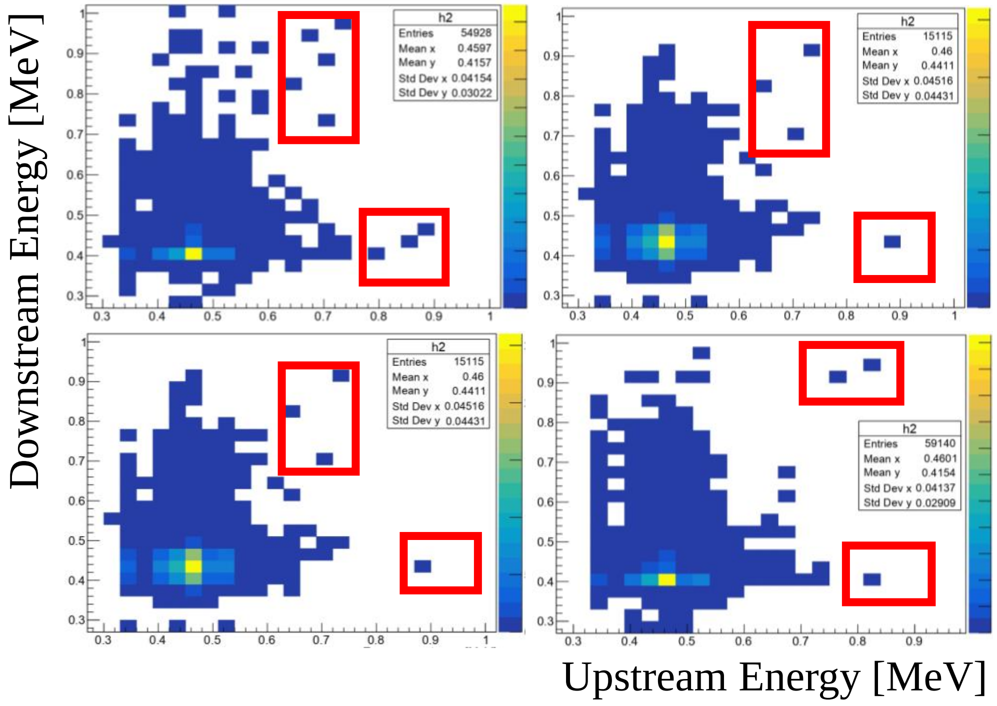


Still possible for **4 MeV**

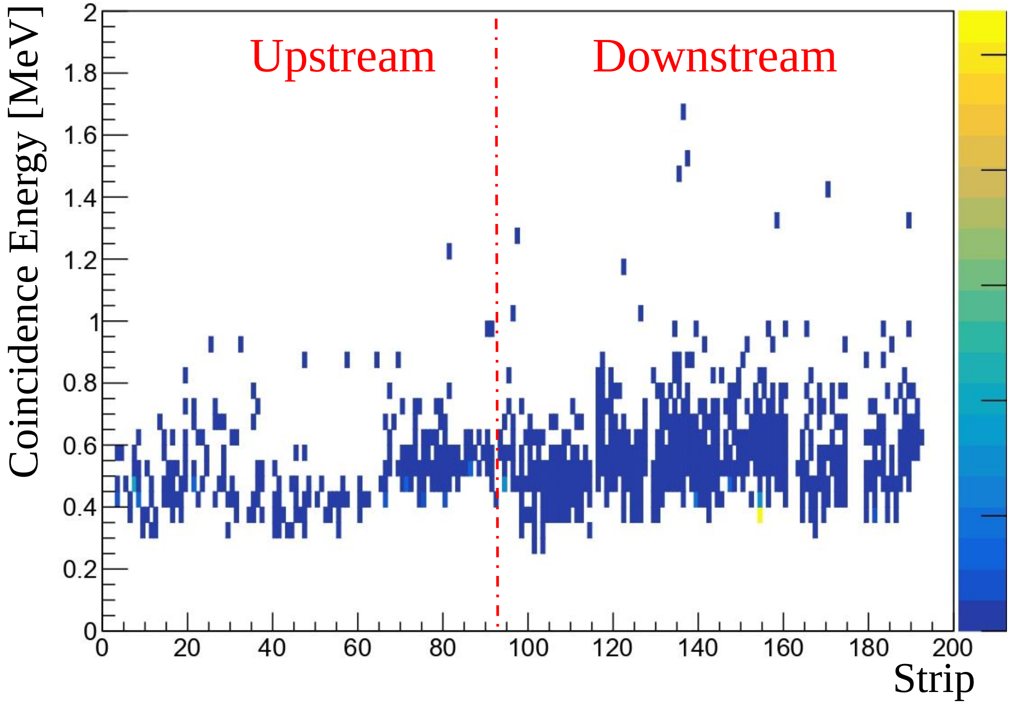


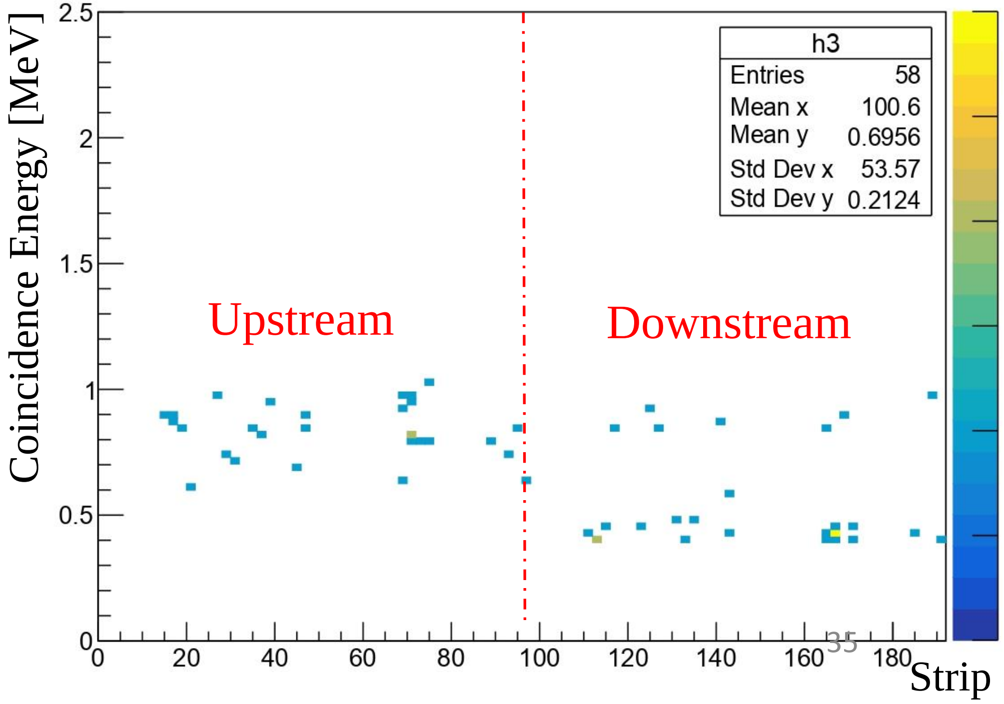




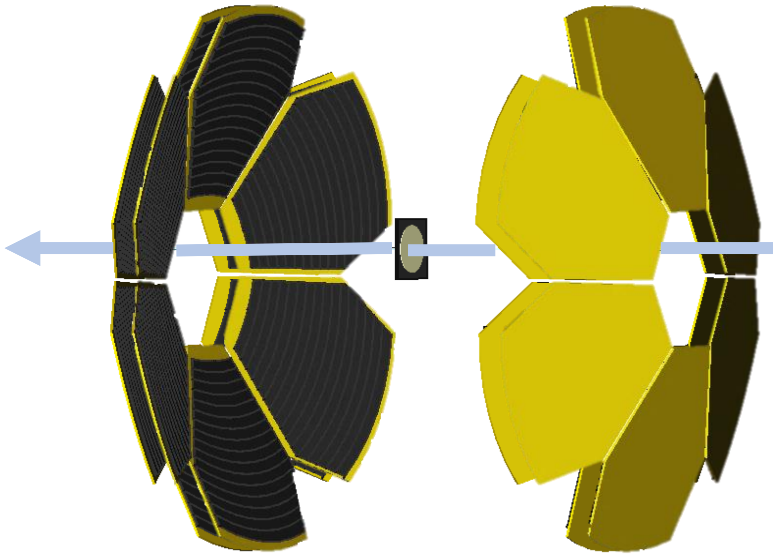


Difficult to distinguish for **3.7 MeV**





p – process

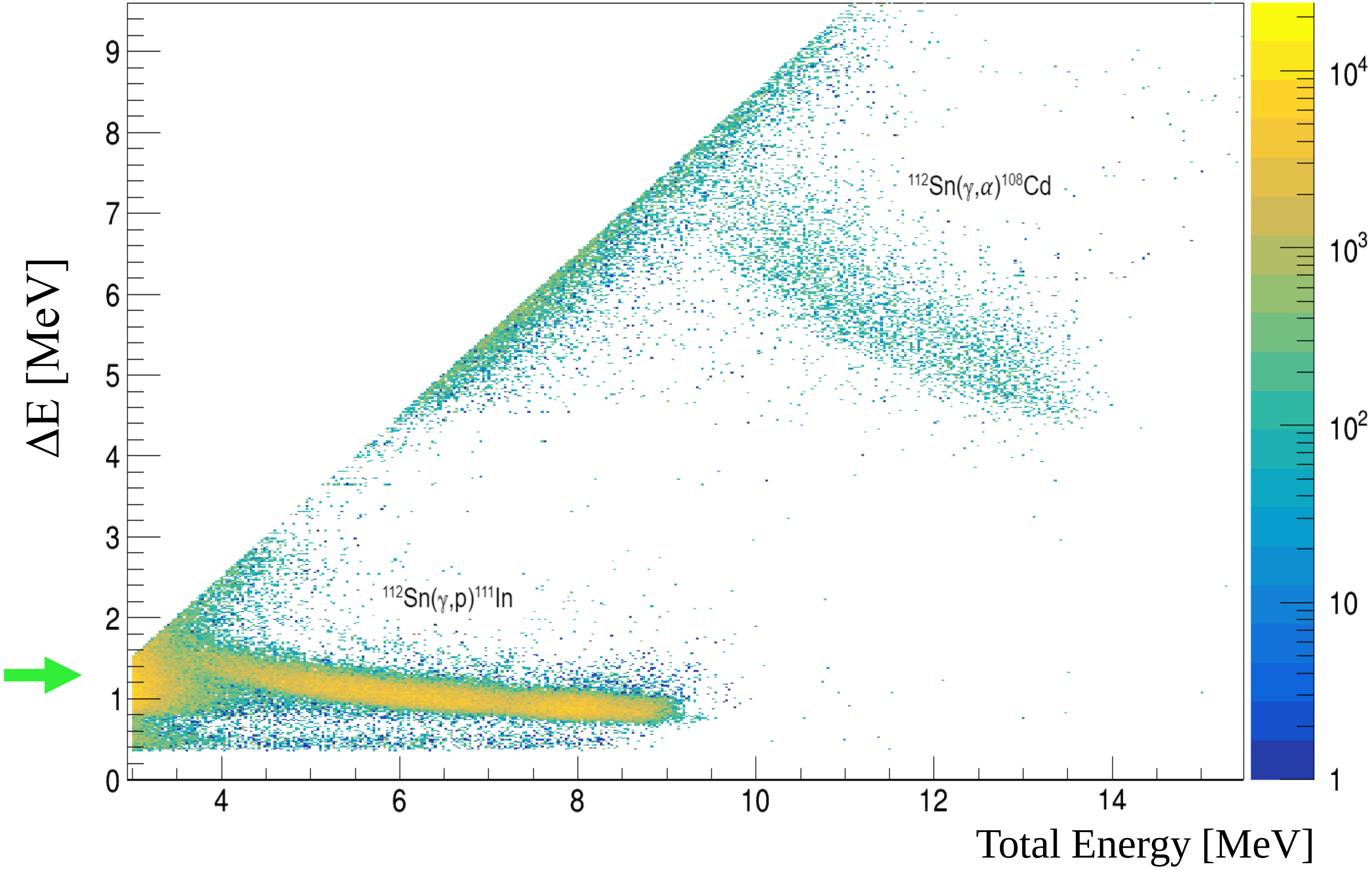


$^{102}Pd(\gamma,p)^{101}Rh$

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

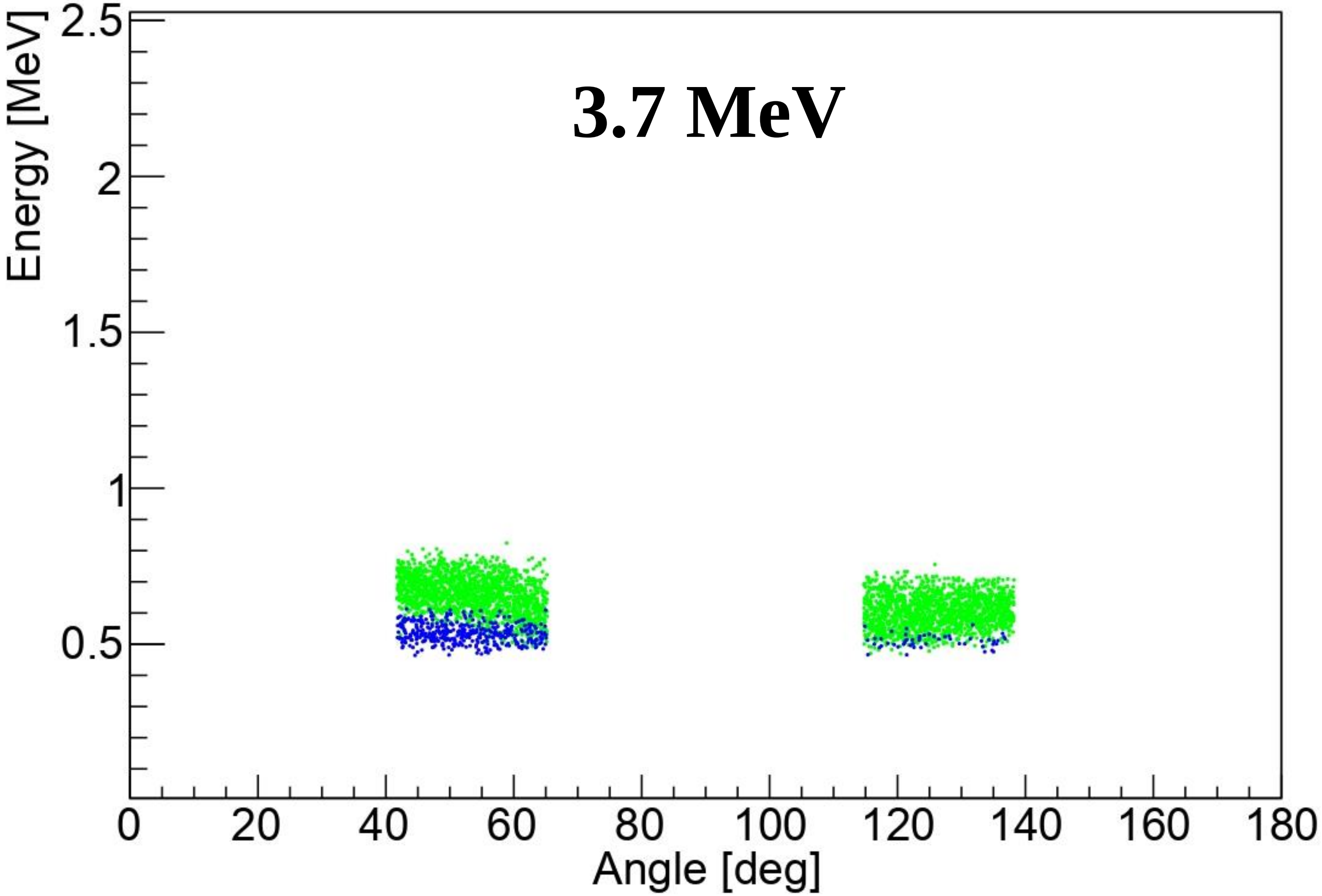
$^{112}Sn(\gamma,p)^{111}In$

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



Monte-Carlo Simulation Code for reactions with charged particles detection

VIKAR (FORTRAN)



Beam

Charged
or
neutral

Target

Mono/Multi-layer foil
or
Gas jet

Detectors

Resistive
or
non-resistive
Si detectors
(telescopes)

Common geometries
and
real-word arrays

Effects: beam spot size and energy spread, energy loss and straggling in targets and detectors, detector segmentation, resolution effects

Monte-Carlo Simulation Code for reactions with charged particles detection

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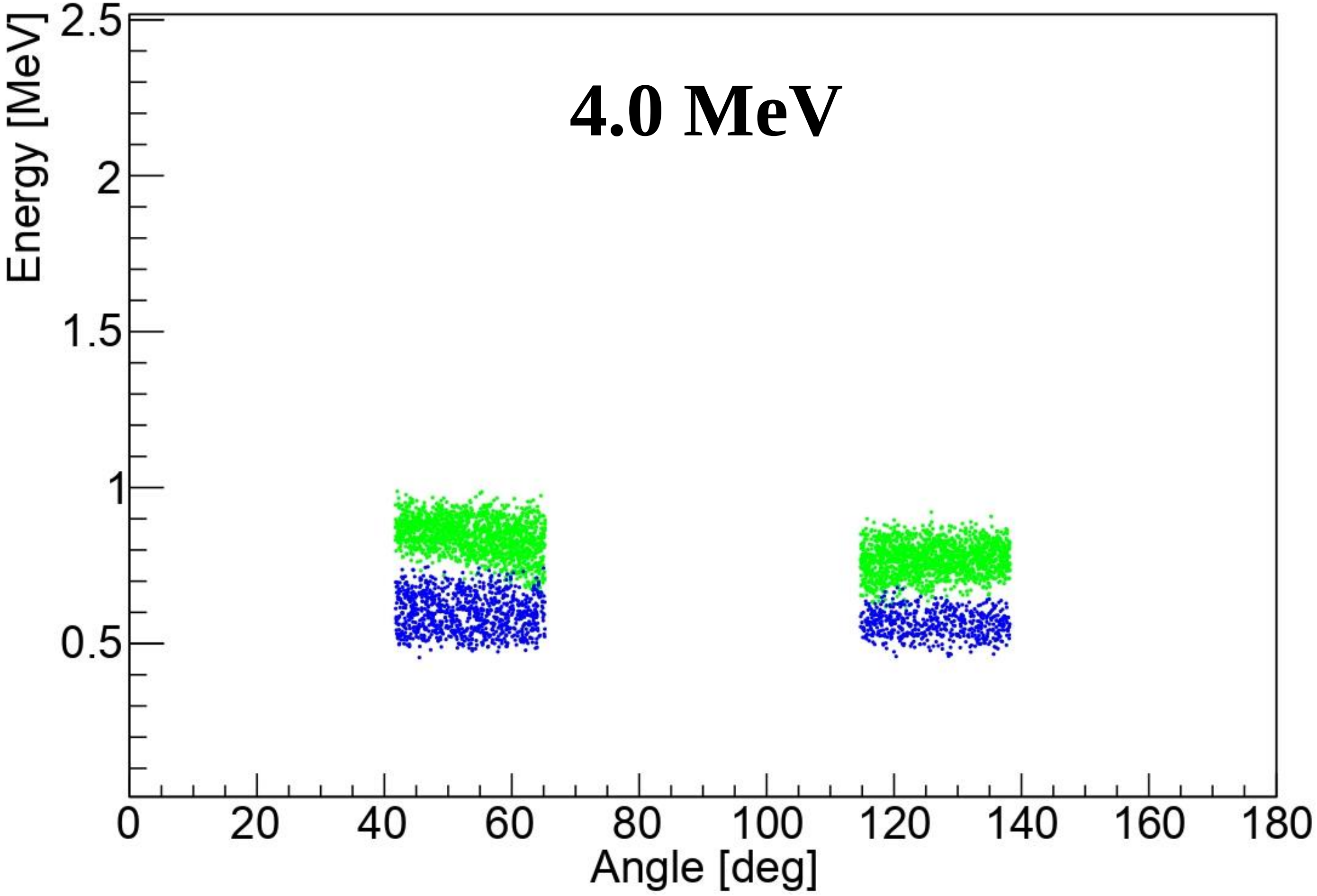

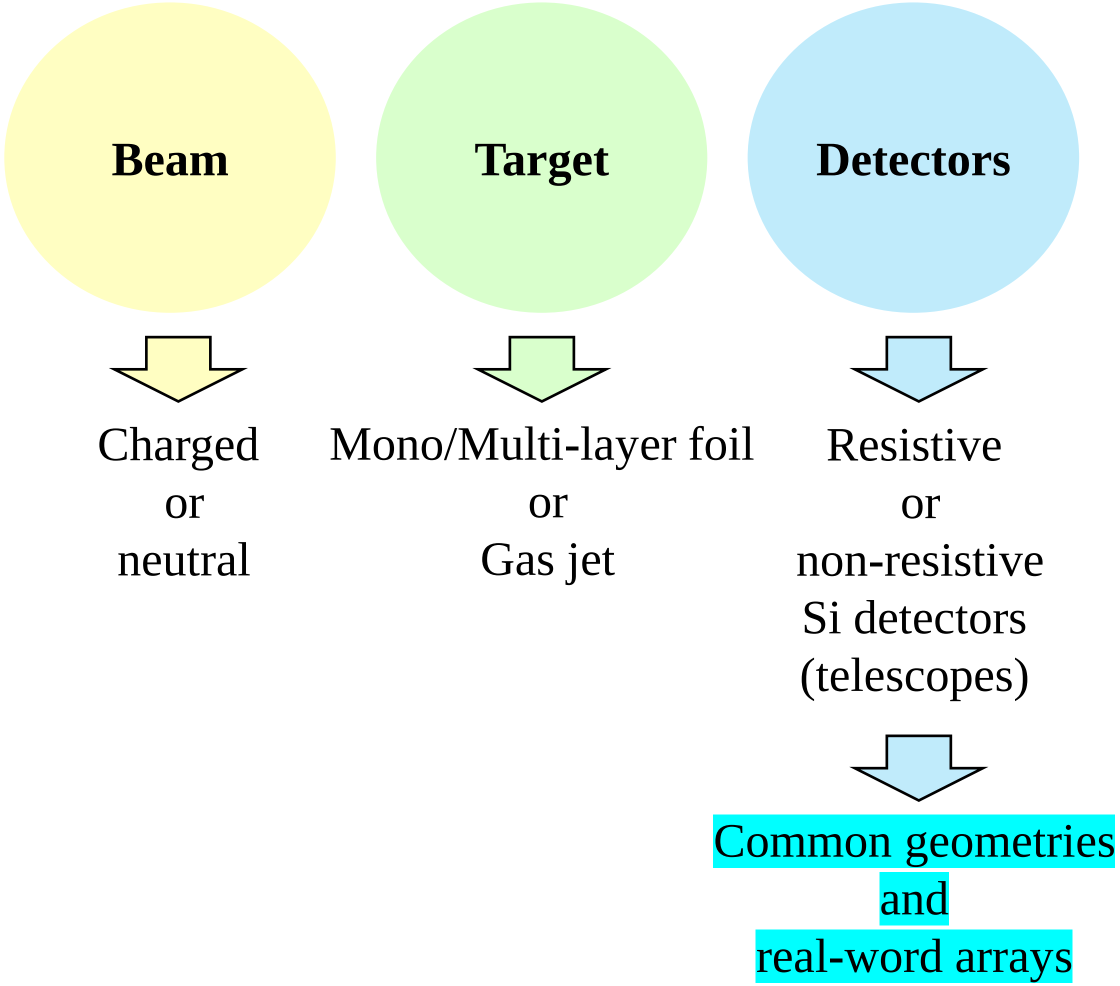

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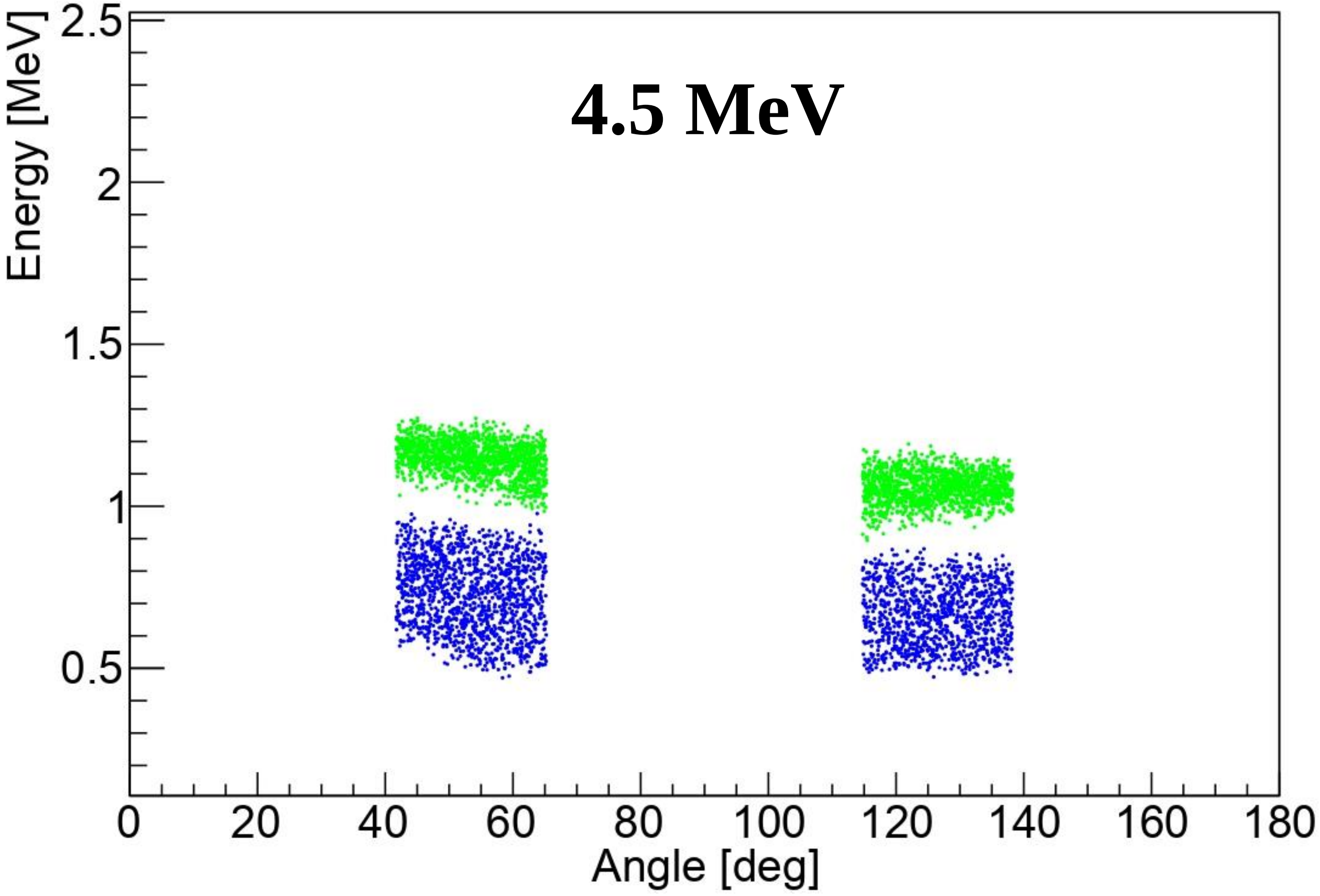

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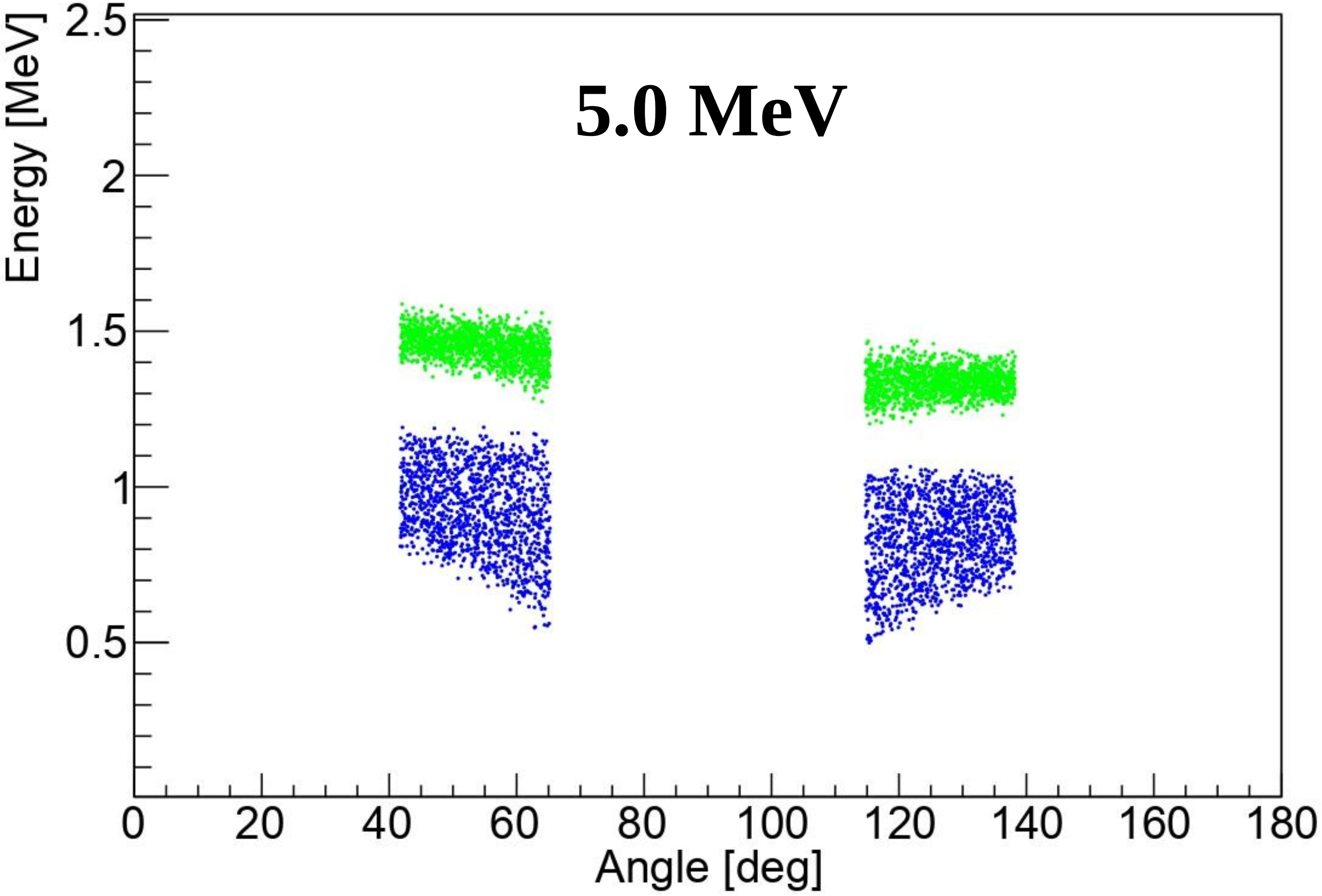

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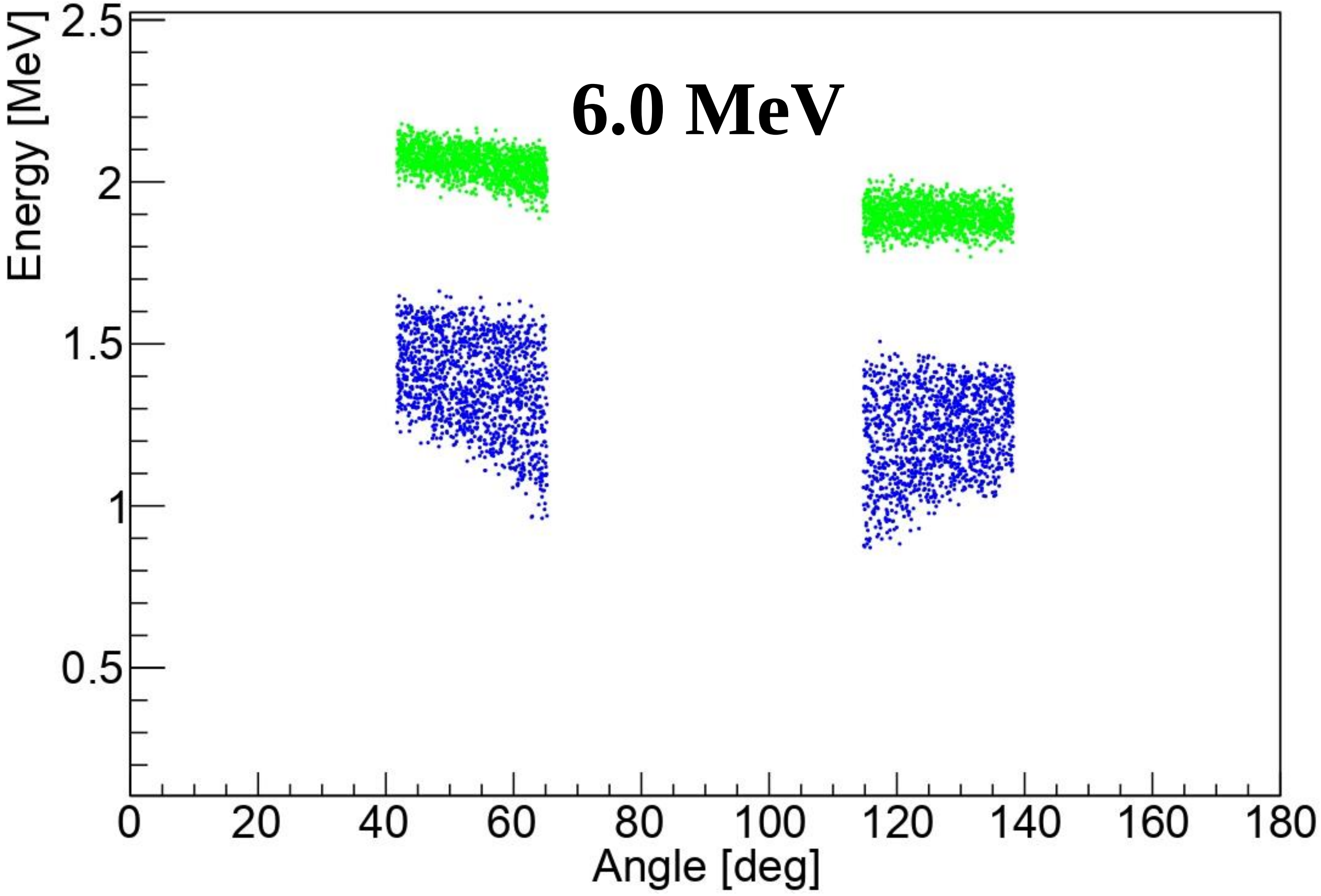

Beam	Target	Detectors
Charged or neutral	Mono/Multi-layer foil or Gas jet	Resistive or non-resistive Si detectors (telescopes)

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