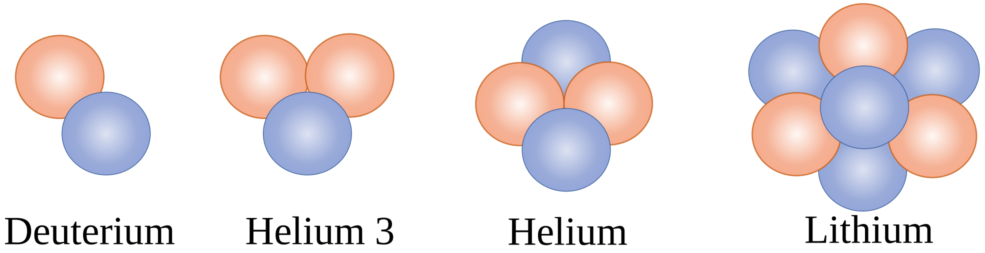
The ^{7}Li photodisintegration below 6 MeV at HIγS

Ioana KUNCSER
GDED

Young Researchers & Young Engineers Days - 2025

The astrophysical motivation of the study

The light elements have been produced in the early stages of the Universe



BBN predictions

&

low metallicity stars observations

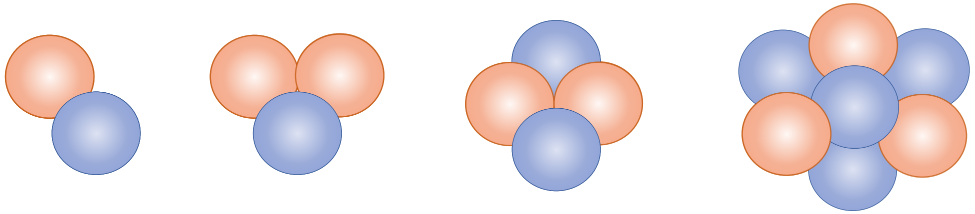
The light elements have been produced in the <u>early stages of the Universe</u>

↓

BBN predictions

&

low metallicity stars observations

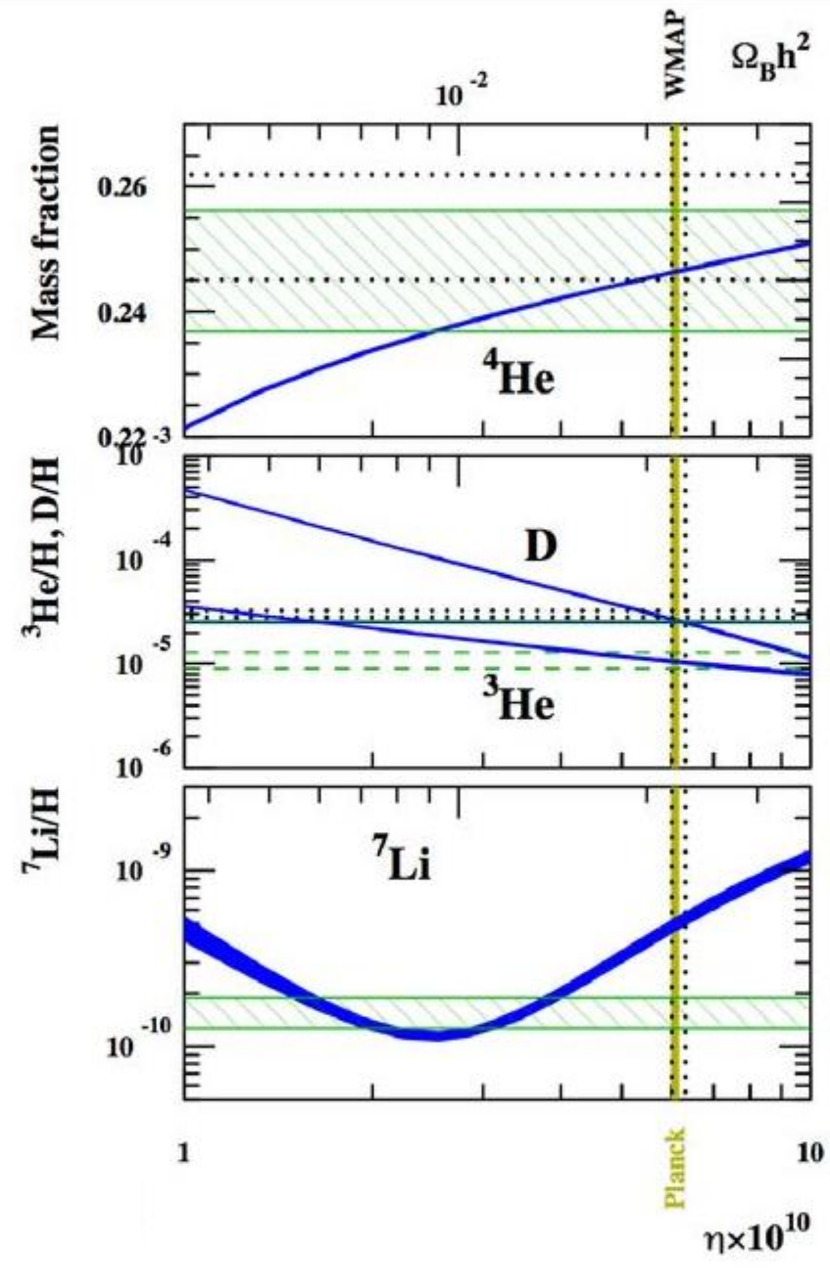


Deuterium Helium 3 Helium Lithium

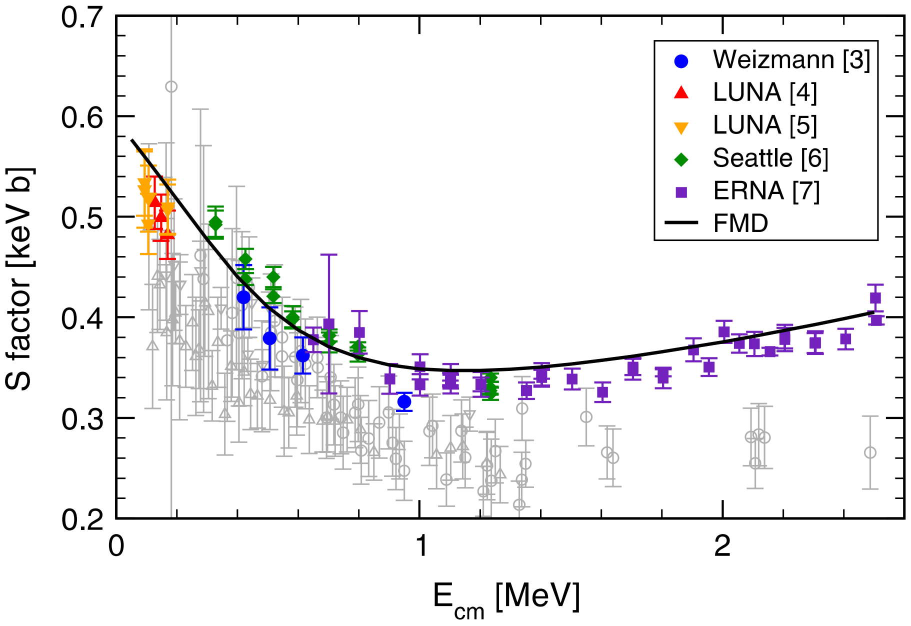
^{7}Li observed abundance is 3-4 times lower than expected from BBN

↓ ↓

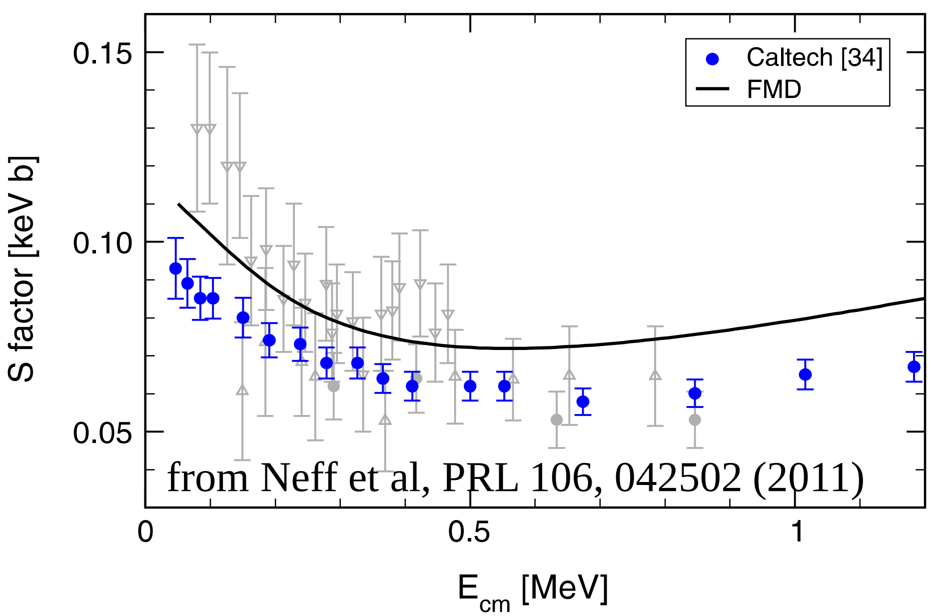
COSMOLOGICAL Li PROBLEM



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



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



1994: $^3H\ (\alpha,\gamma)\ ^7Li$ reaction at low energies

target *beam* *detection with Ge detectors (<3.7 MeV)*

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

1994: ${}^{3}H\,(\alpha,\gamma)\,{}^{7}Li$ reaction at low energies ($E_\gamma <$ 3.7 MeV)

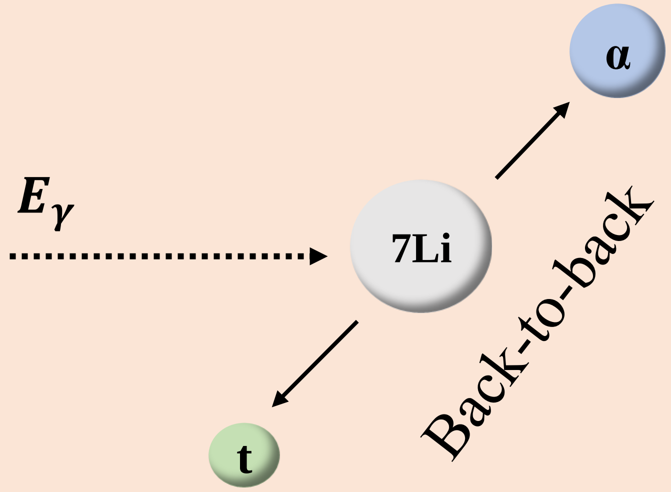
target *beam* *detection with Ge det*

THE RECIPROCITY THEOREM:

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

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

$$\boldsymbol{\sigma_{{}^{7}Li\gamma\to\alpha t} \sim 100 \cdot \sigma_{\alpha t\to {}^{7}Li\gamma}}$$



2017 and 2023: ${}^{7}Li\,(\gamma,\alpha)\,{}^{3}H$ reaction (E_γ: 3.7 - 10 MeV)

target *beam* *detection with Si detector array*

2017 and 2023: $^{7}Li\,(\gamma,\alpha)\,^{3}H$ reaction (E_{γ}: 3.7 - 10 MeV)

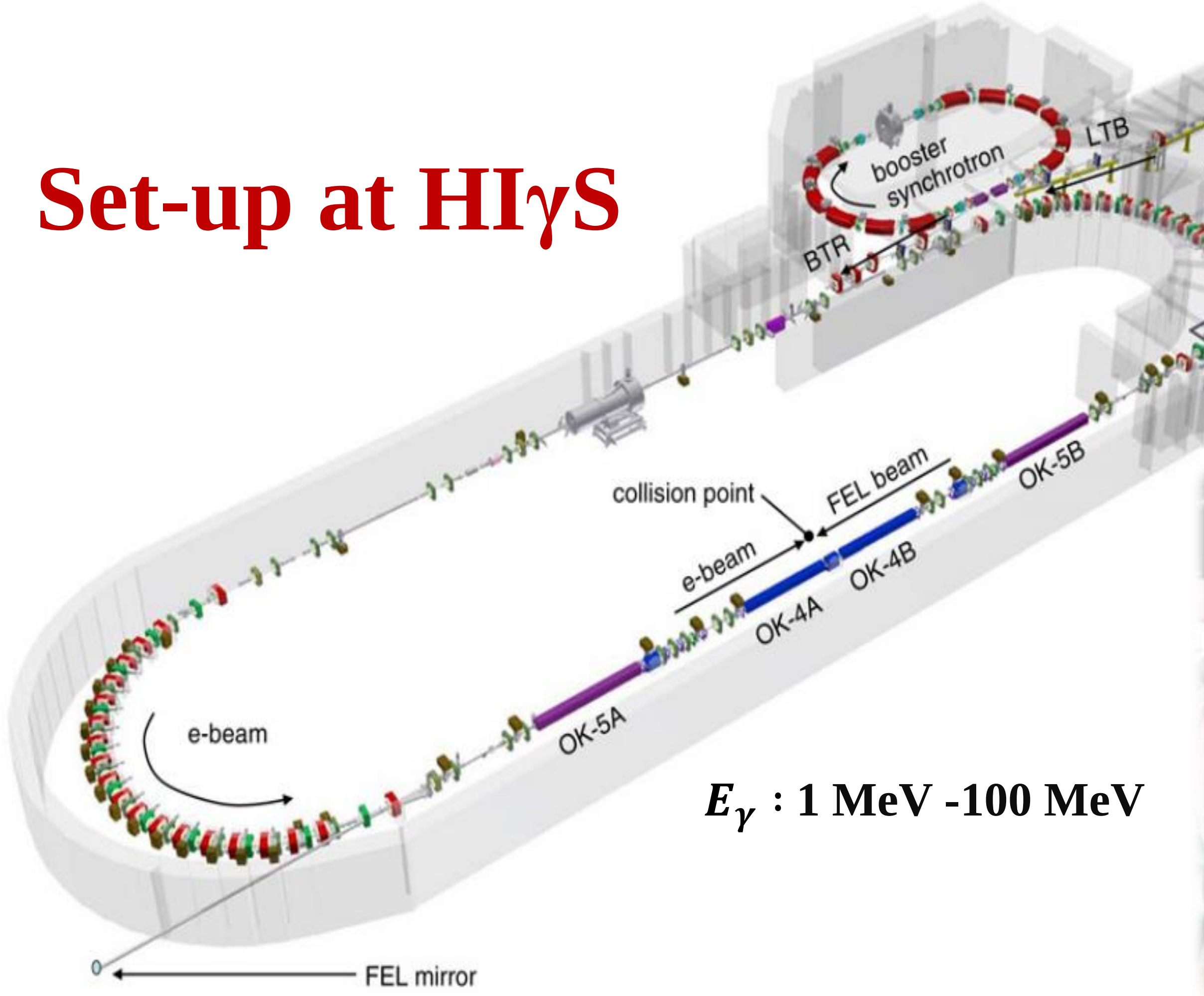
target — ^{7}Li

beam — γ

detection with Si detector array — α, ^{3}H

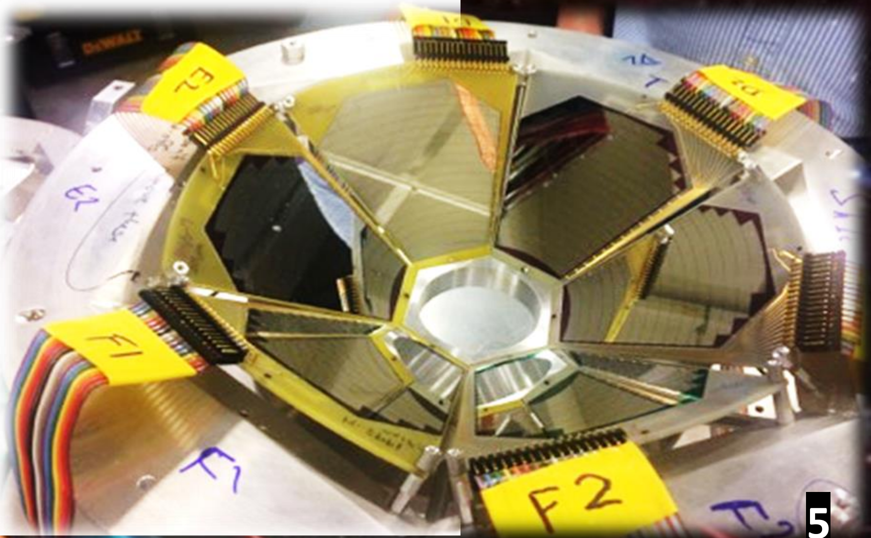
LiF/Mylar

Set-up at HIγS



E_{γ} : 1 MeV -100 MeV

SIDAR

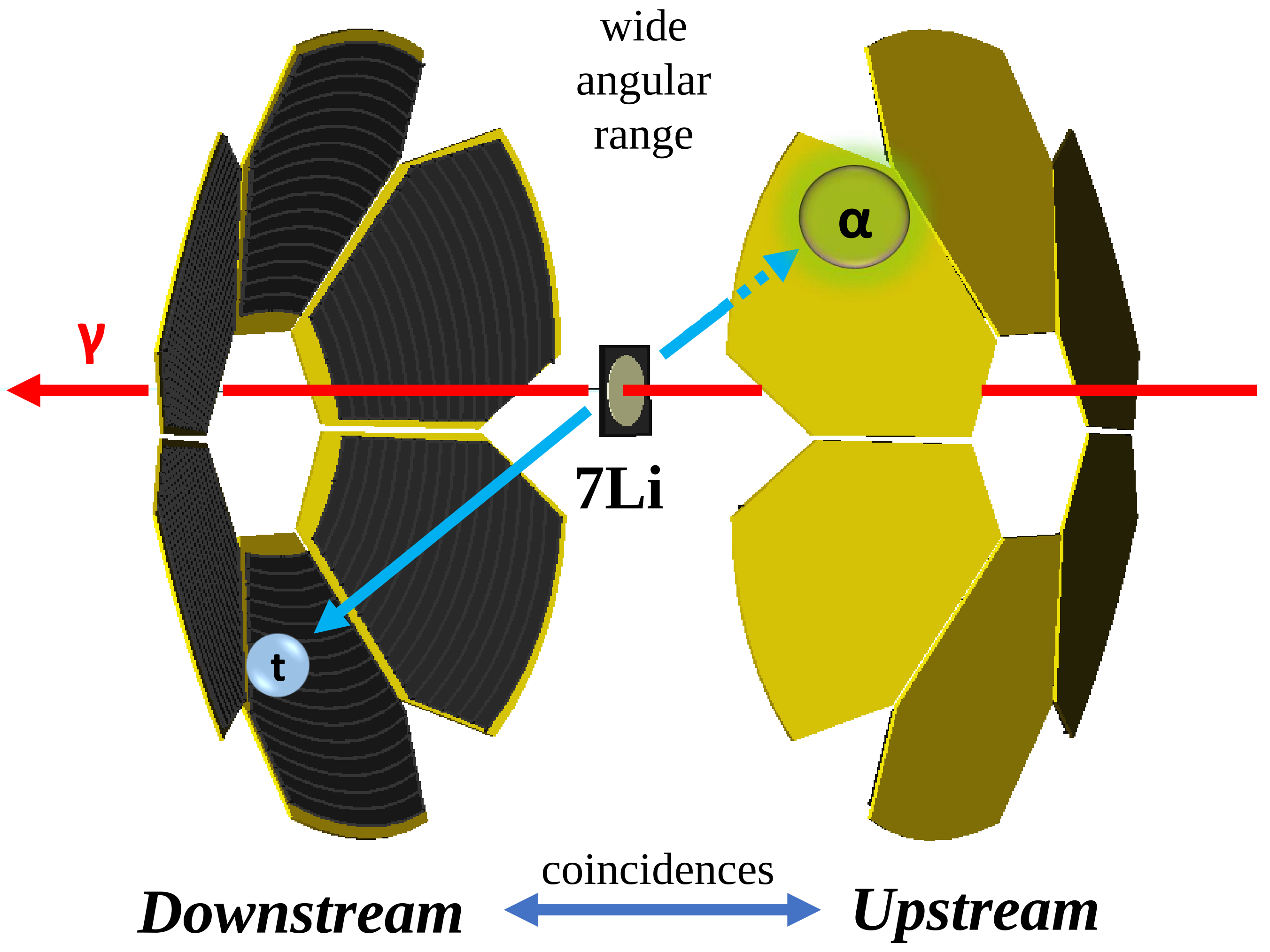


SIDAR: SIlicon Detector ARray

~ 38.66%

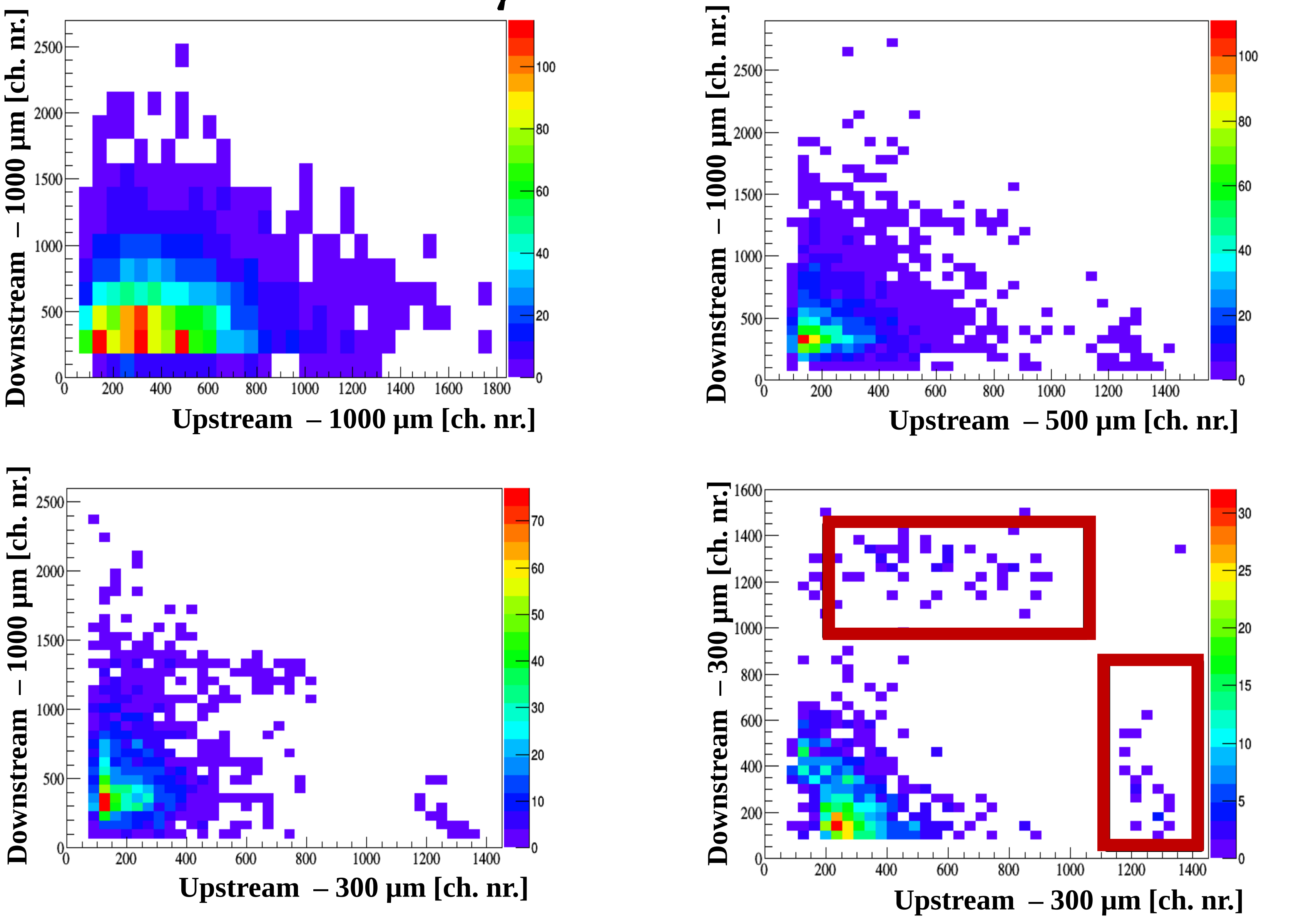
geometric

efficiency



2 x 6 YY1
(16 strips)
↓
192 channels

$E_\gamma = 4.4$ MeV

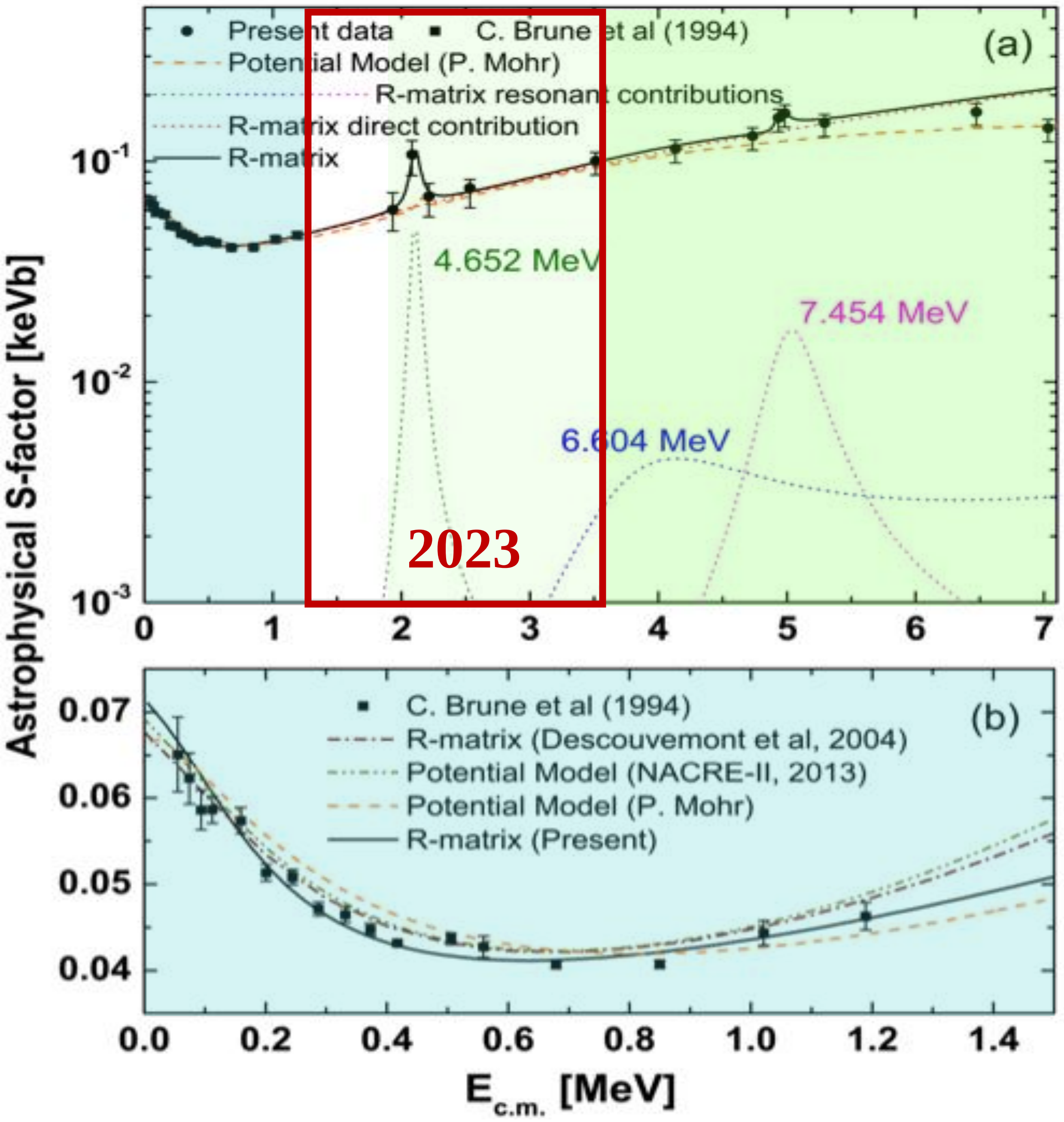


2017:

The measurement of the $^{7}Li\,(\gamma,\alpha)\,^{3}H$ reaction

E_γ: **4.4 – 10.0 MeV**

Below 6 MeV the coincidences have been separated only in the thinner detectors



April 2023:

A new measurement of the $^{7}Li\ (\gamma,\alpha)\ ^{3}H$ reaction

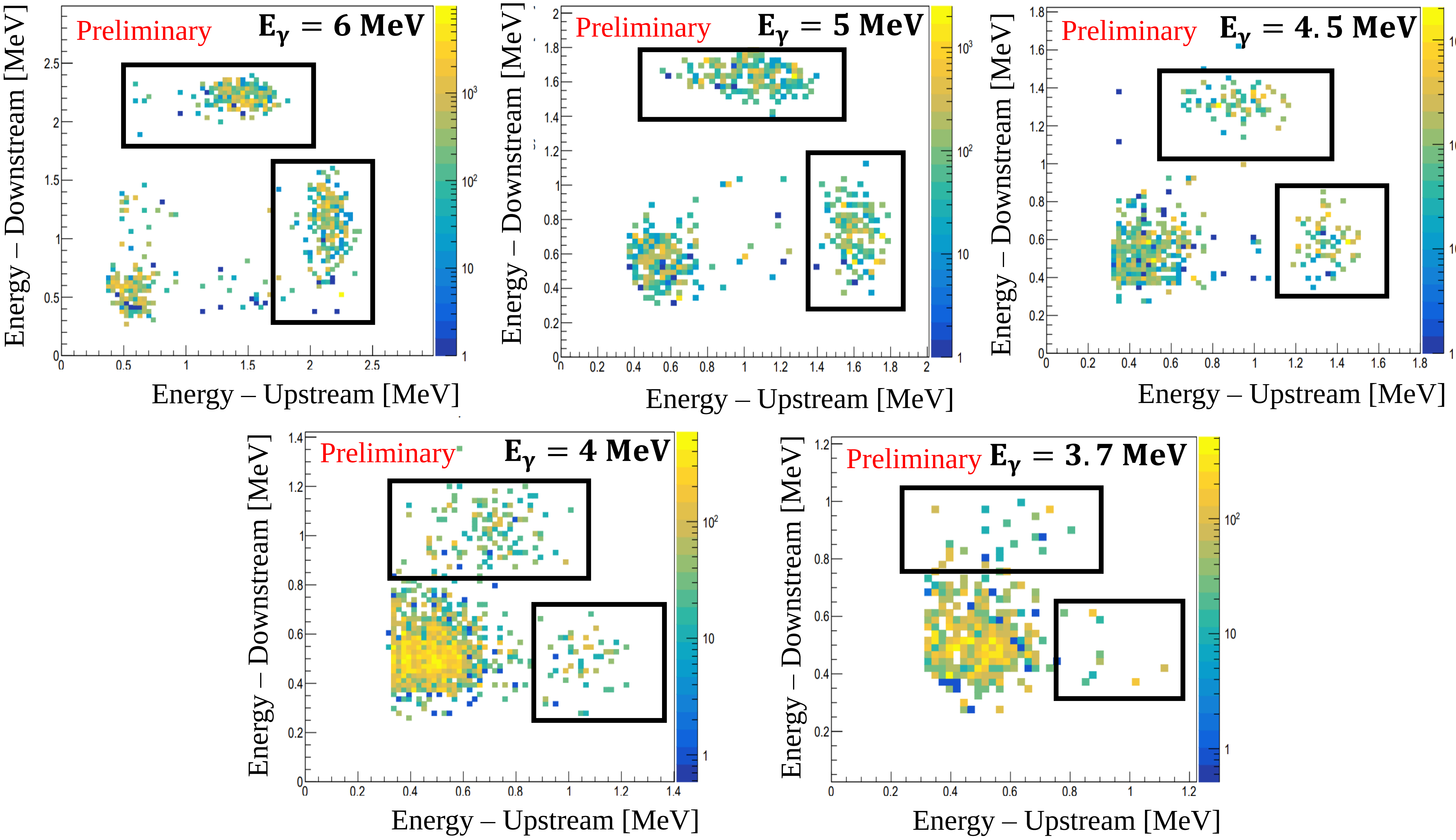
E_{γ}: 3.7 – 6.0 MeV

IMPROVEMENTS

Thinner Si detectors: 100 (d) &65 (u) µm

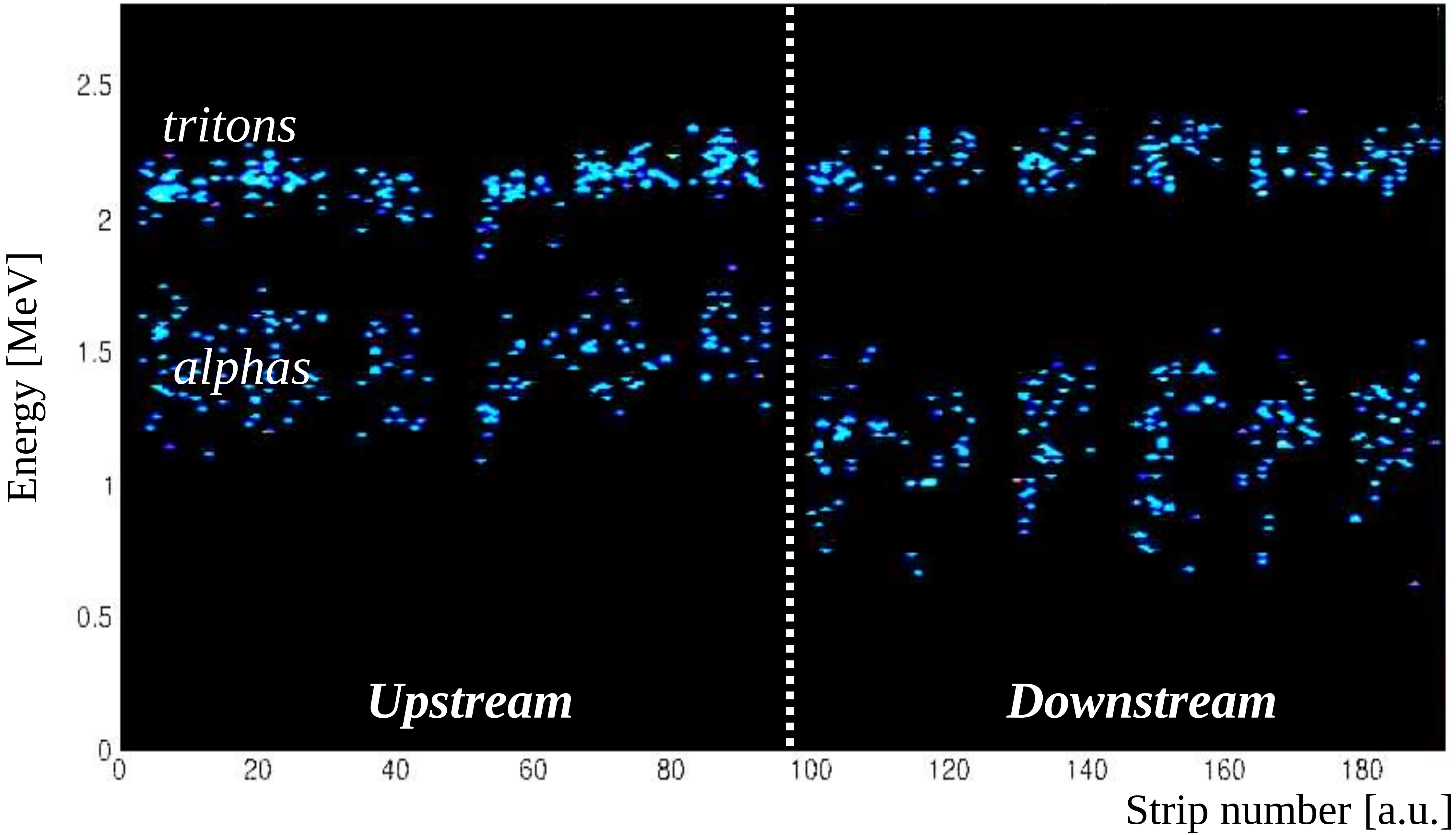
Thinner entry flange (Al)

Longer vacuum pipe (in front of the chamber)

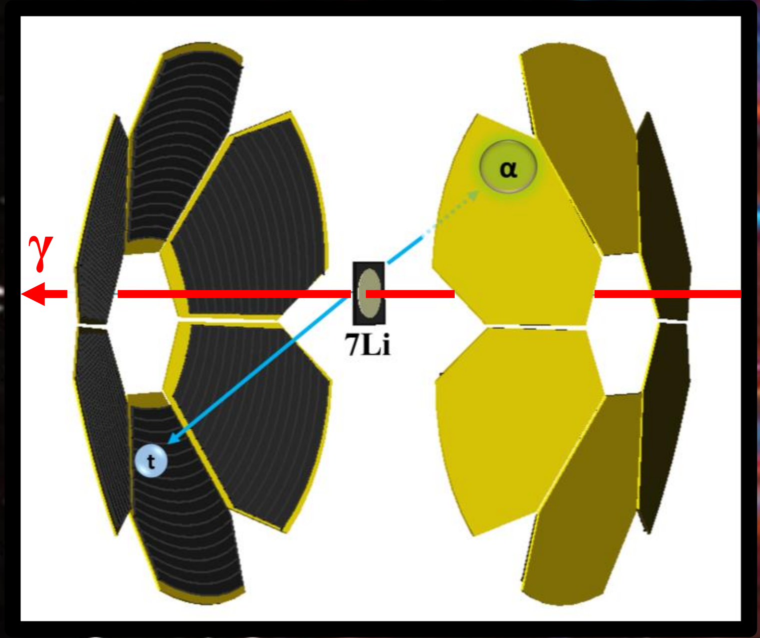


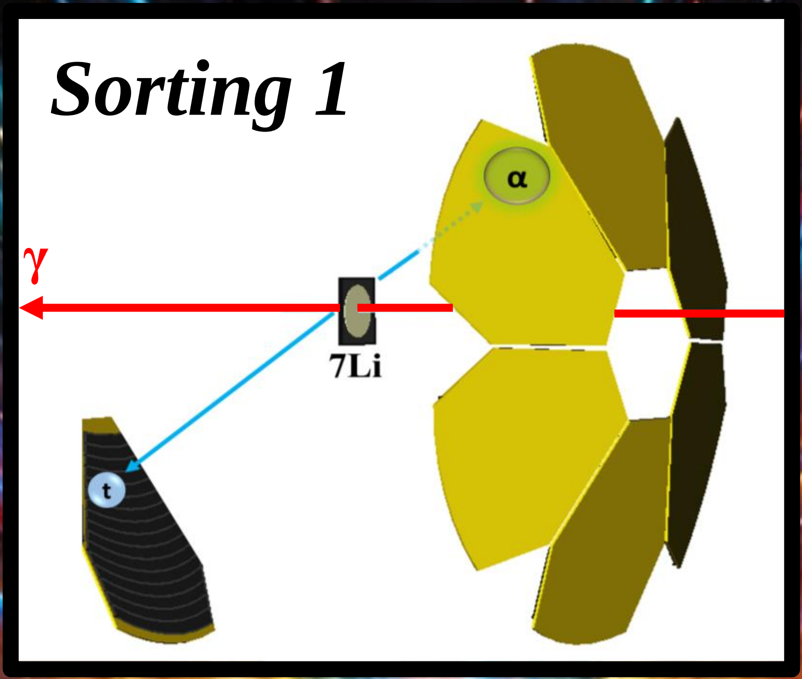
Preliminary
$E_\gamma = 6$ MeV
Preliminary
$E_\gamma = 5$ MeV
Preliminary
$E_\gamma = 4.5$ MeV
Preliminary
$E_\gamma = 4$ MeV
Preliminary
$E_\gamma = 3.7$ MeV
Energy – Downstream [MeV]
Energy – Upstream [MeV]

6 MeV after background subtraction



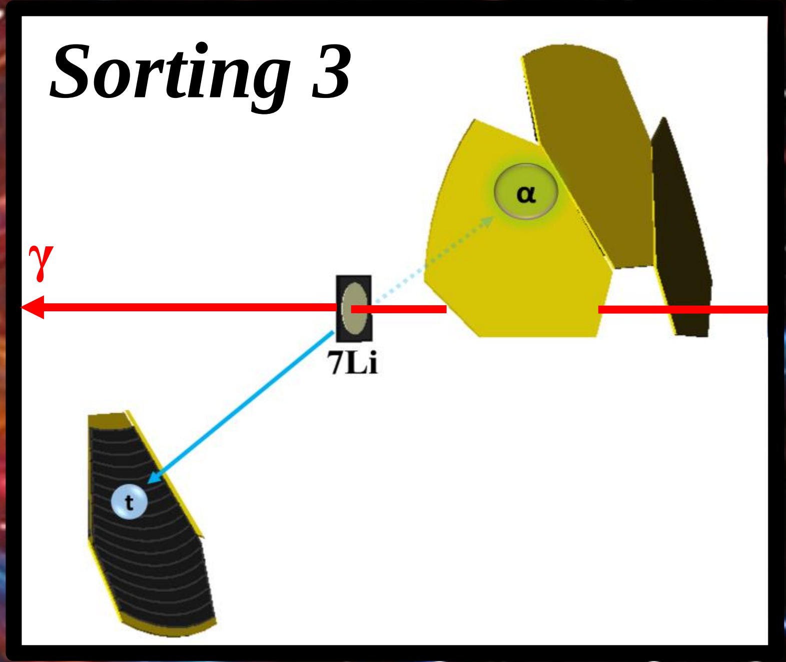
First estimation →
extremely noisy results



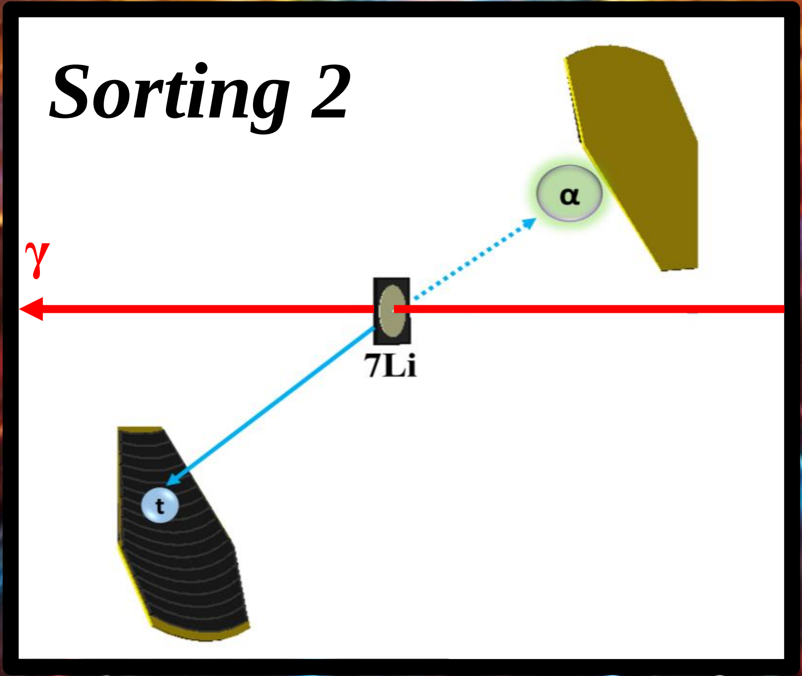


First improvement →
noisy results

Compromise between background
subtraction and counting accuracy

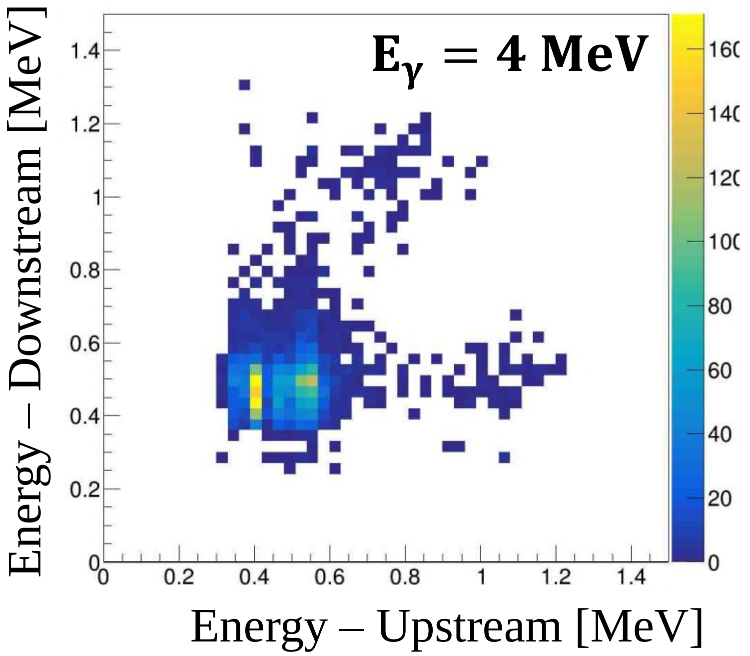


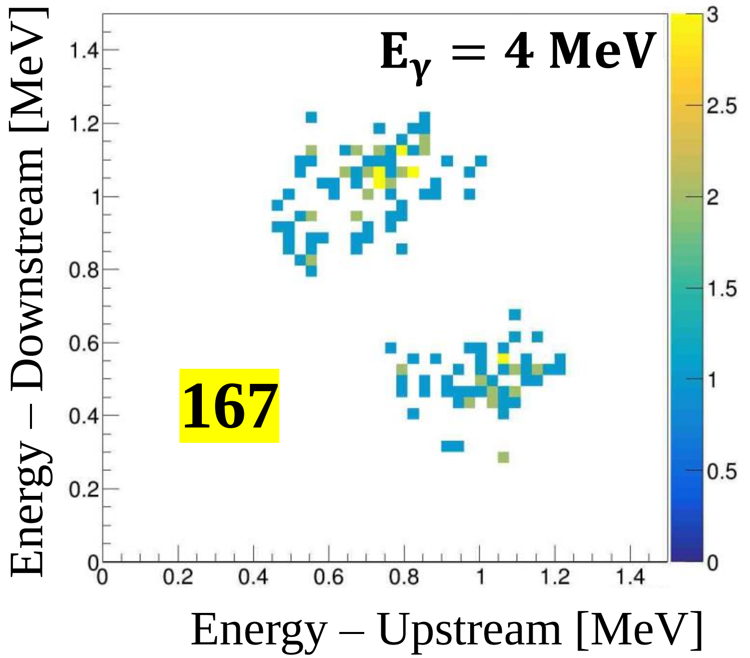
Third Improvement→
quiet clear results



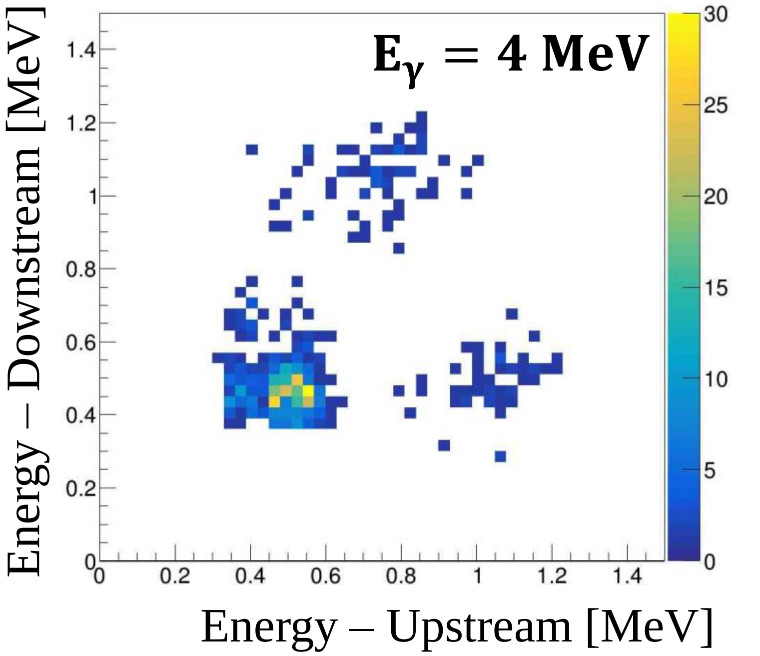
Second improvement→
very clear results

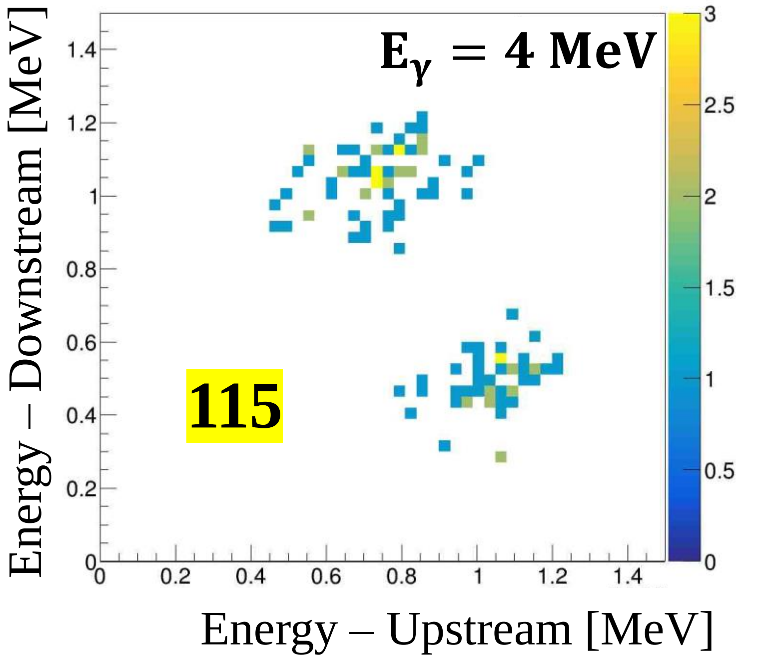
Sorting 1



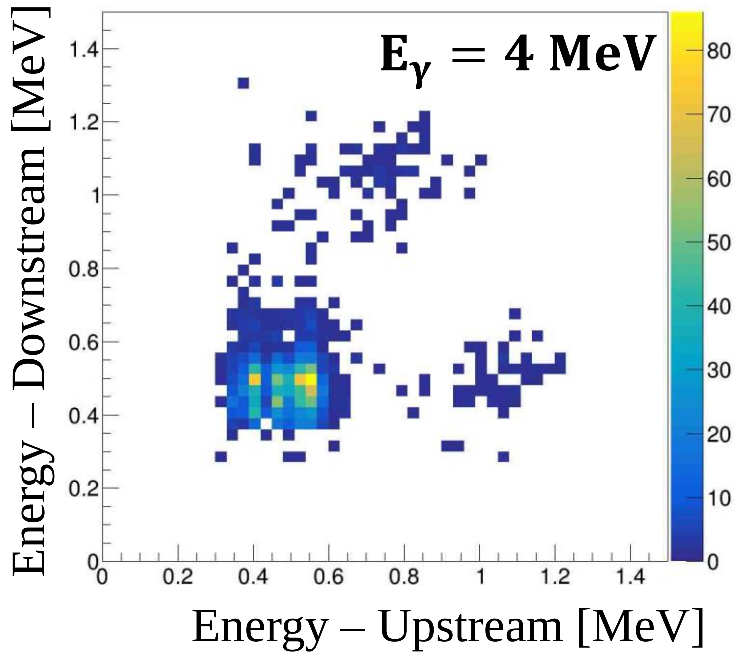


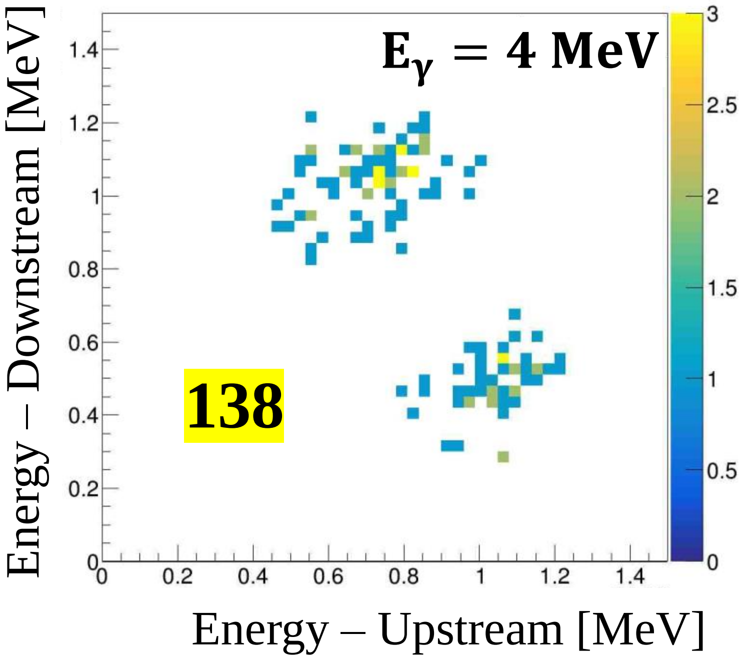
Sorting 2





Sorting 3



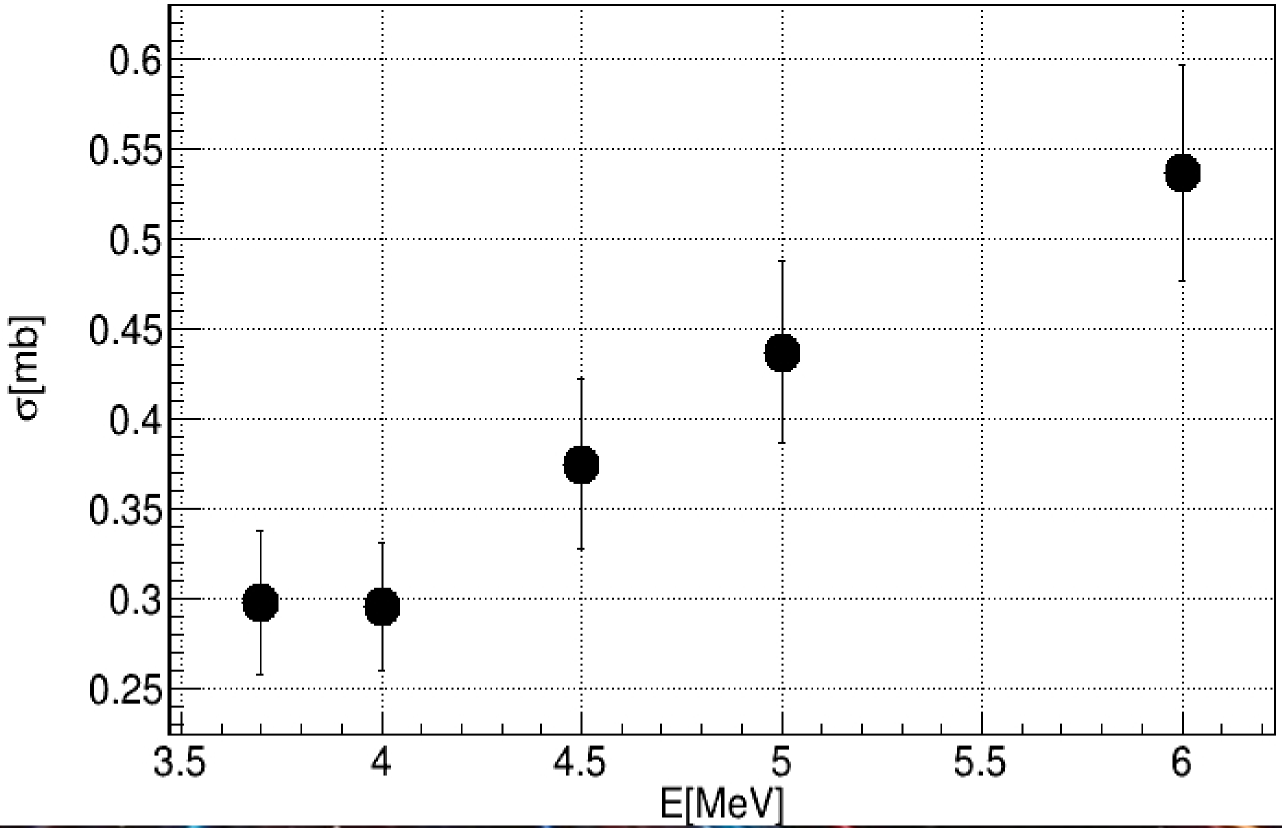


The ground state cross-section of the inverse $^{7}Li\ (\gamma, \alpha)\ ^{3}H$ reaction

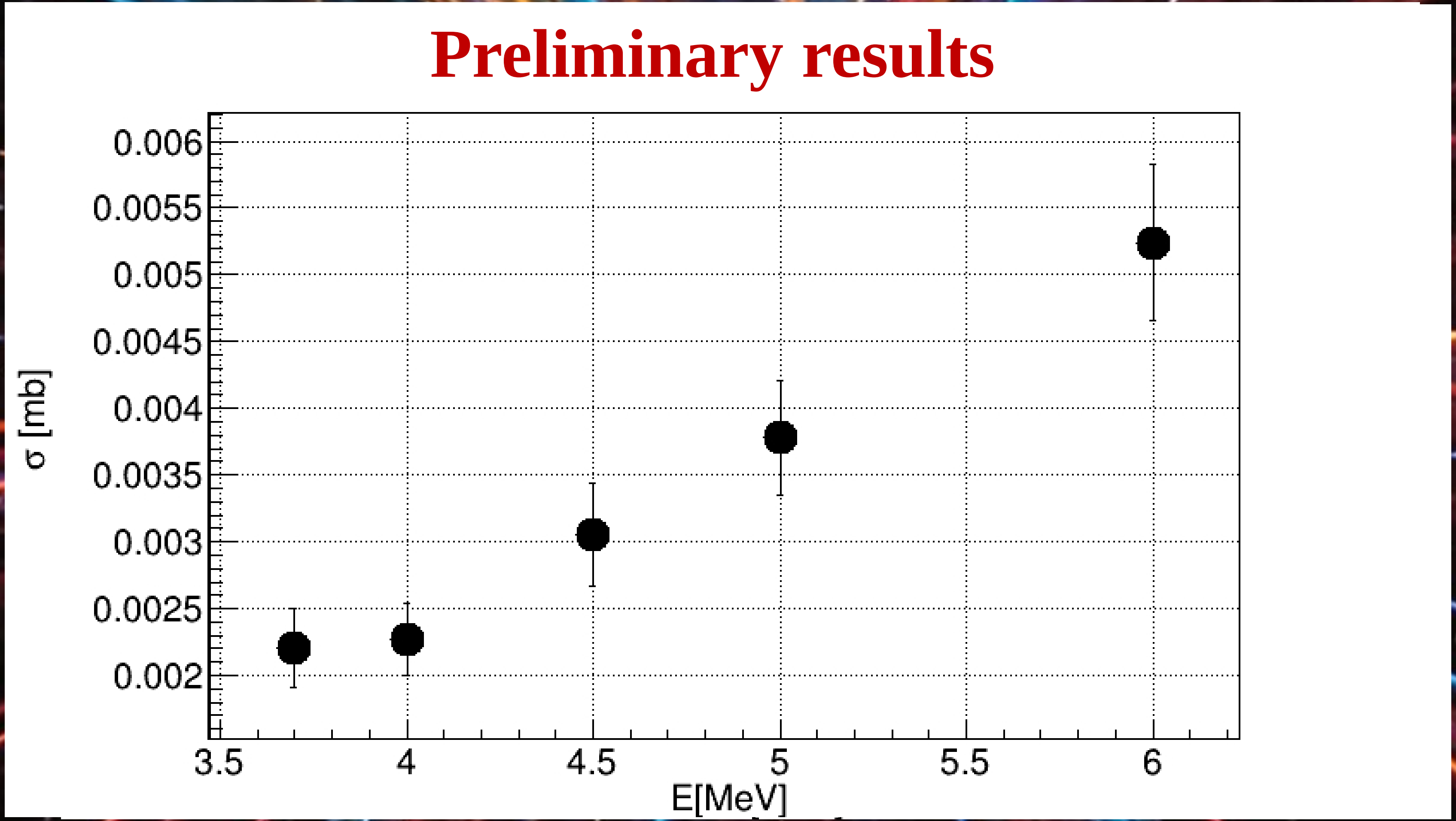
$$\sigma = \frac{R}{N_{beam} \cdot N_{target} \cdot \varepsilon}$$

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

Preliminary results



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

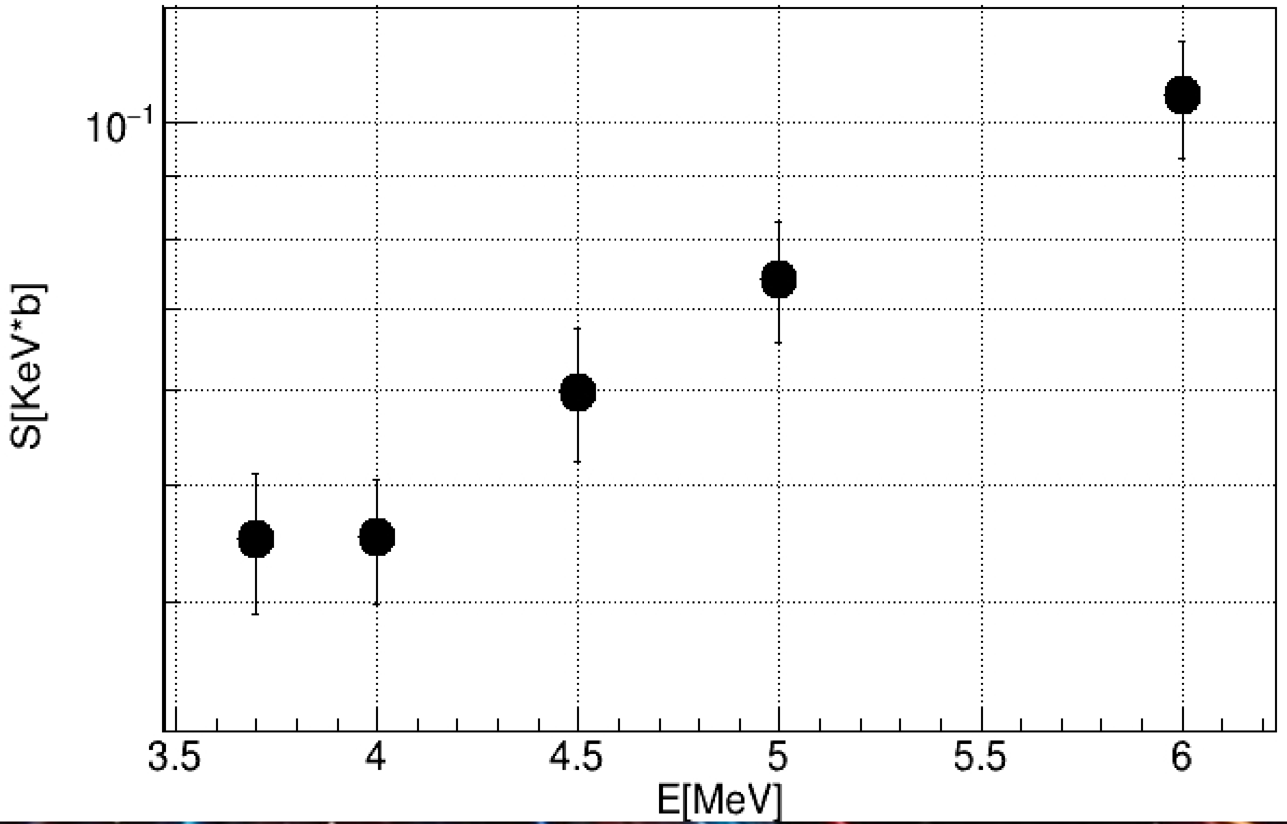


The Astrophysical S-factor of the direct $^{3}H\,(\alpha,\gamma)\,^{7}Li$ reaction

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

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

Preliminary results



R-matrix

AZURE2 (Fortran 77)

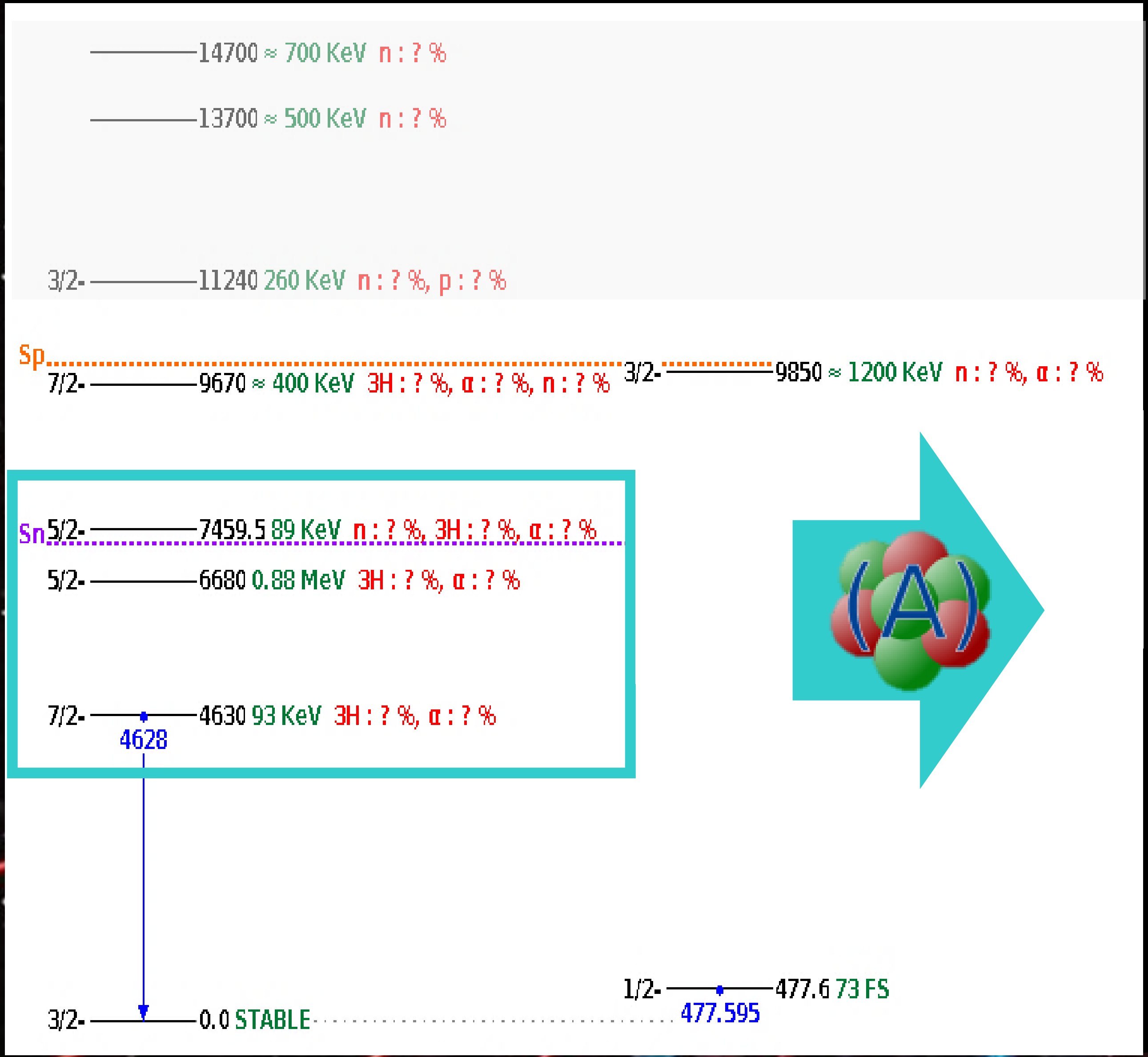
describes two-body reactions by adjusting the parameters of the nuclear structure

parameters mostly related to the energies and the partial widths of the nuclear levels

developed for R-matrix calculations

suitable for low-energy nuclear reactions involving charged particles, photons and neutrons

Lithium 7 nuclear levels scheme

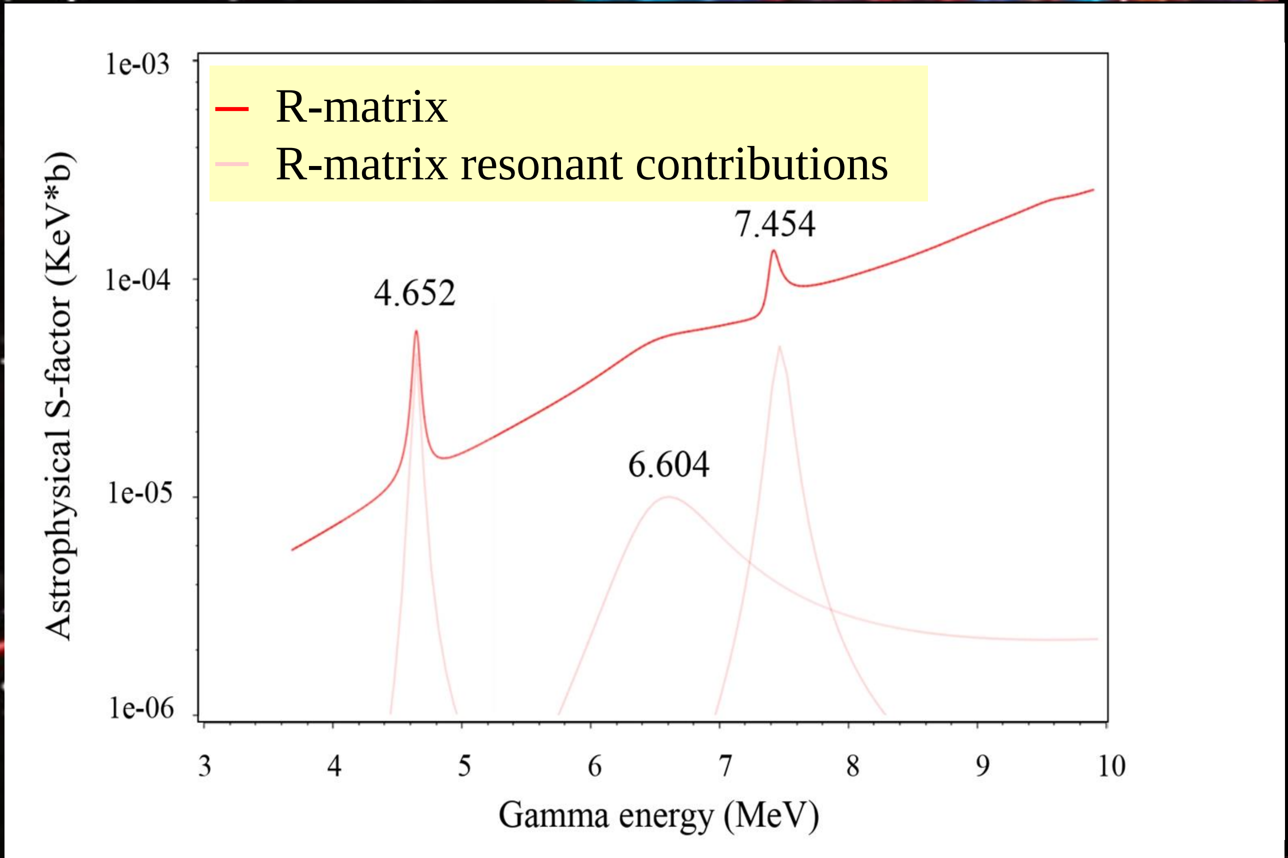


Measurement of the $^{7}Li\,(\gamma,t)\,^{4}He$ ground-state cross section between E_{γ}= 4.4 and 10 MeV, M. Munch, C. Matei, S.D. Pain, K.A. Chipps, et al., Phys. Rev. C 101, 055801 (2020)

E[MeV]	J^{π}	Γ_{α}[MeV]	$\Gamma_{\gamma}[eV]$
0	3/2 -	ANC=3.4$fm^{1/2}$	μ=3.256 nm
0.4776	1/2 -	ANC=3.1 $fm^{1/2}$	
4.652	7/2 -	0.069	0.09
6.604	5/2 -	0.918	0.27
7.454	5/2 -	0.17	0.29
9.09	7/2 -	0.91	2.5
10	1/2 -	9.24	370
10	1/2 +	10.6	
10	3/2 +	10.4	13
10	5/2 +	10.0	3

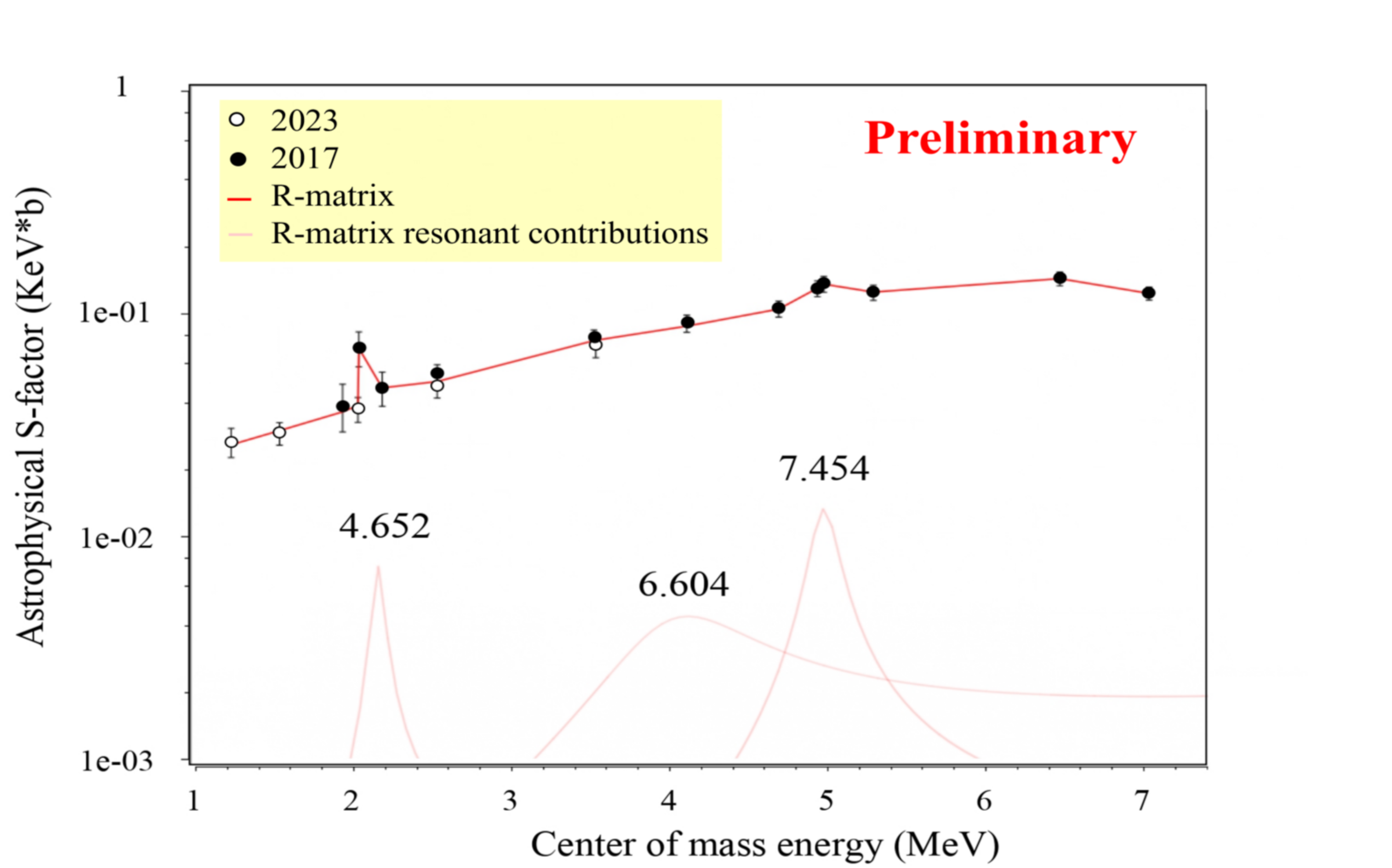
R-matrix – AZURE2

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



E[MeV]	J^π	Γ_α[MeV]	$\Gamma_\gamma[eV]$
0	3/2 -	ANC=3.4$fm^{1/2}$	μ=3.256 nm
0.4776	1/2 -	ANC=3.1 $fm^{1/2}$	
4.652	7/2 -	0.069	0.09
6.604	5/2 -	0.918	0.27
7.454	5/2 -	0.17	0.29
9.09	7/2 -	0.91	2.5
10	1/2 -	9.24	370
10	1/2 +	10.6	
10	3/2 +	10.4	13
10	5/2 +	10.0	3

R-matrix applied on the 2023 and 2017 data



Conclusions:

The reaction $^{3}H\ (\alpha,\gamma)\ ^{7}Li$ is important due to the discrepancy between the theoretical models and the experimental data and is more efficiently studied through its inverse reaction

HIγS, 2017: The ^{7}Li phodisintegration for E_{γ}: 4.4 - 10 MeV using a Si detector array → below 6 MeV the coincidences have been separated only in the thinner detectors

HIγS, 2023: The ^{7}Li phodisintegration for E_{γ}: 3.7 - 6 MeV using a Si detector array (improved set-up) → clear separation of the coincidences, the background affecting only the lowest energy

The preliminary Astrophysical S-factor has been extracted → A preliminary R-matrix fit (Azure2) has been performed over the results from 2023, together with the results from 2017

Thank you for attention!

- *Catalin Matei, D. Balabanski, Ioana Kuncser, T. Petruse, 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, 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)*

Conclusions:

The reaction $^{3}H\ (\alpha,\gamma)\ ^{7}Li$ is important due to the discrepancy between the theoretical models and the experimental data and is more efficiently studied through its inverse rection.

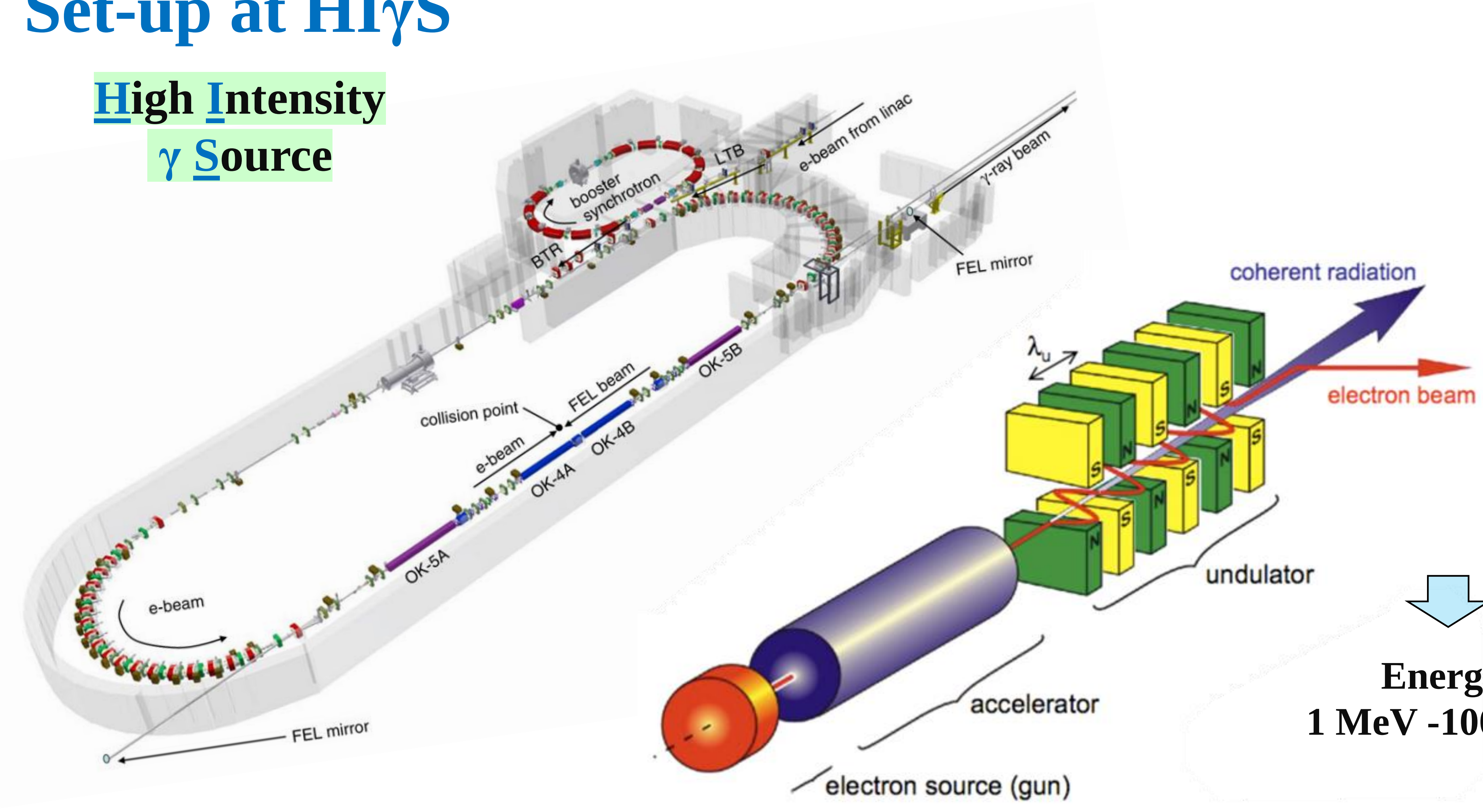
The ^{7}Li phtodisintegration has been studied by our team in 2017 at HIγS for E_{γ}: 4.4 - 10 MeV using a Si detector array.

A new experiment with an improved set-up has been performed in April 2023 at HIγS for E_{γ}: 3.7 - 6 MeV, the background affecting only the lowest energy.

The preliminary Astrophysical S-factor has been extracted. The results from 2023, together with the results from 2017, have been fitted using the Azure 2 code to apply the R-matrix formalism.

Set-up at HIγS

High Intensity
γ Source

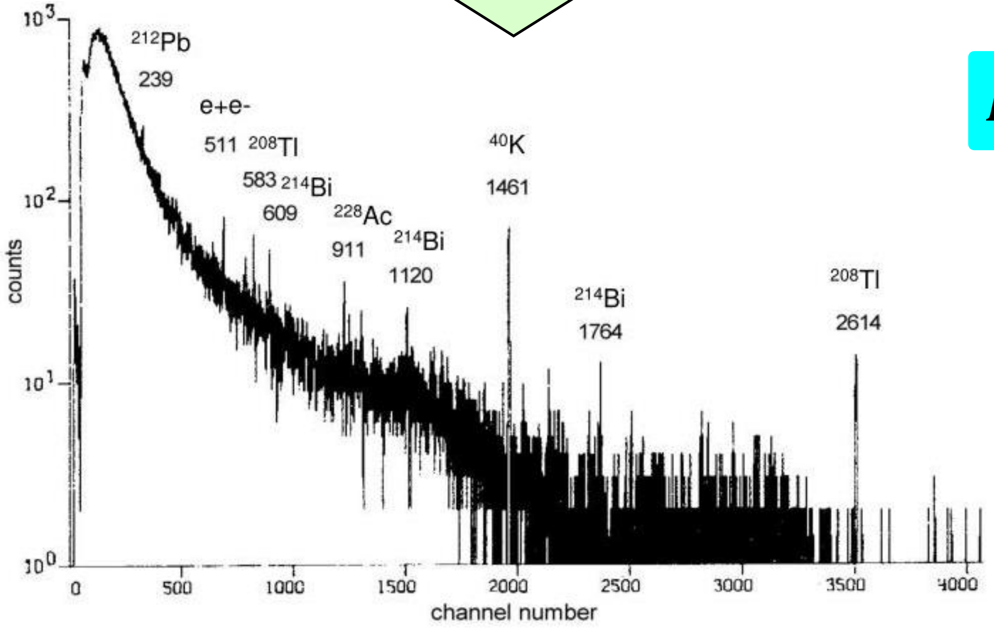


Energy:
1 MeV -100 MeV

Gamma beam energy measurement

Ge DETECTOR + ATTENUATORS

Calibrated using background

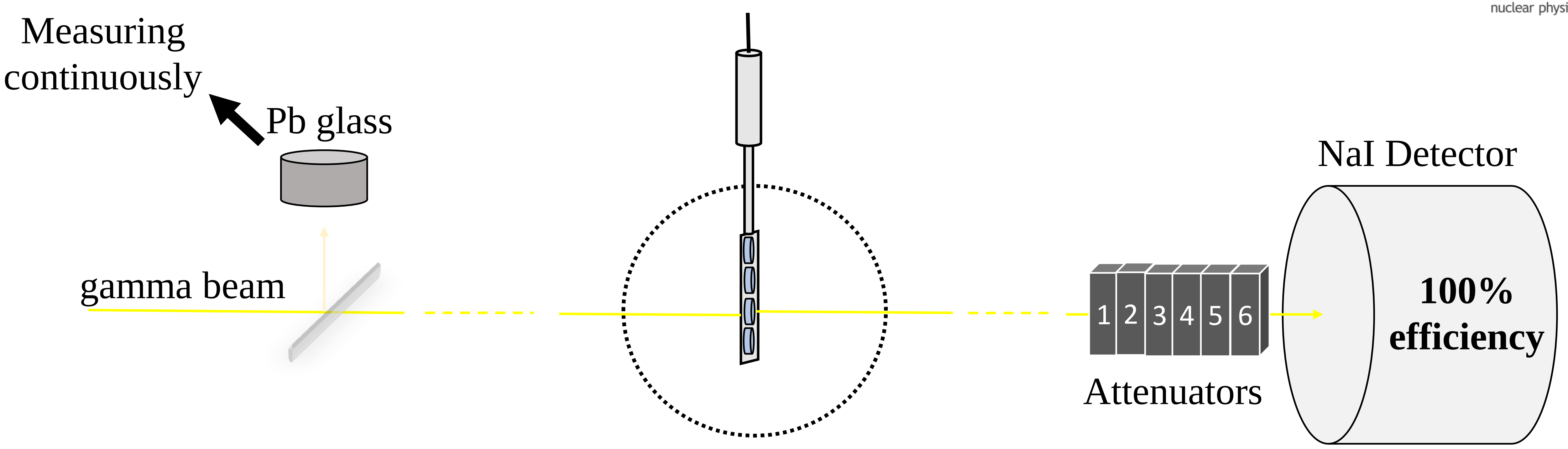


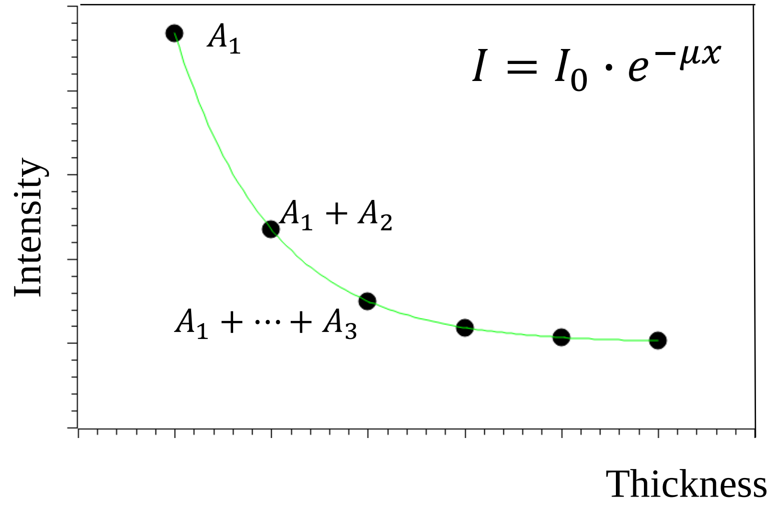
$$E_\gamma = E_{det} + E_{loss}$$

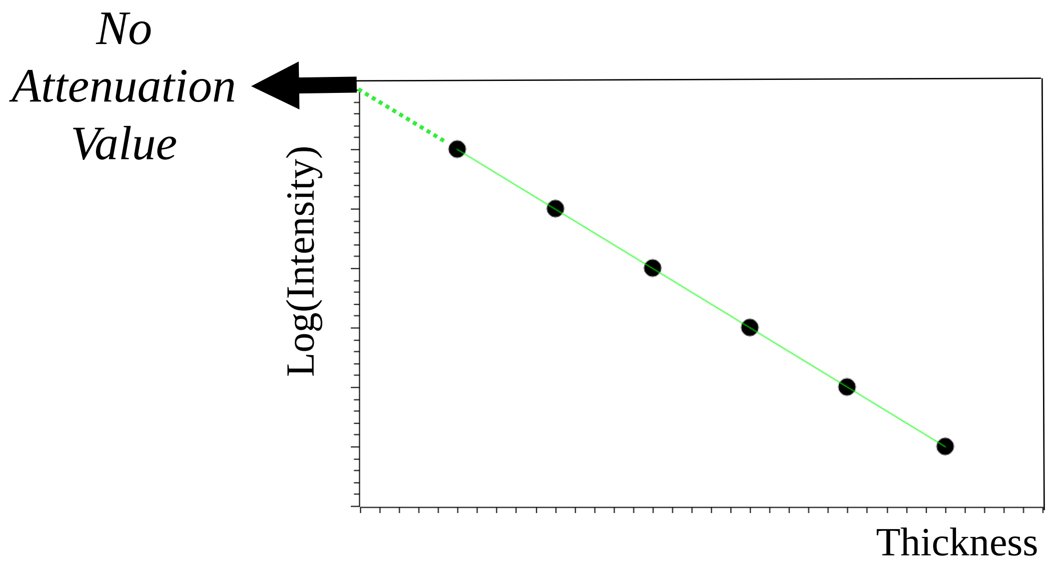
Known energy loss

39.35 cm
of
copper

Gamma beam intensity measurement





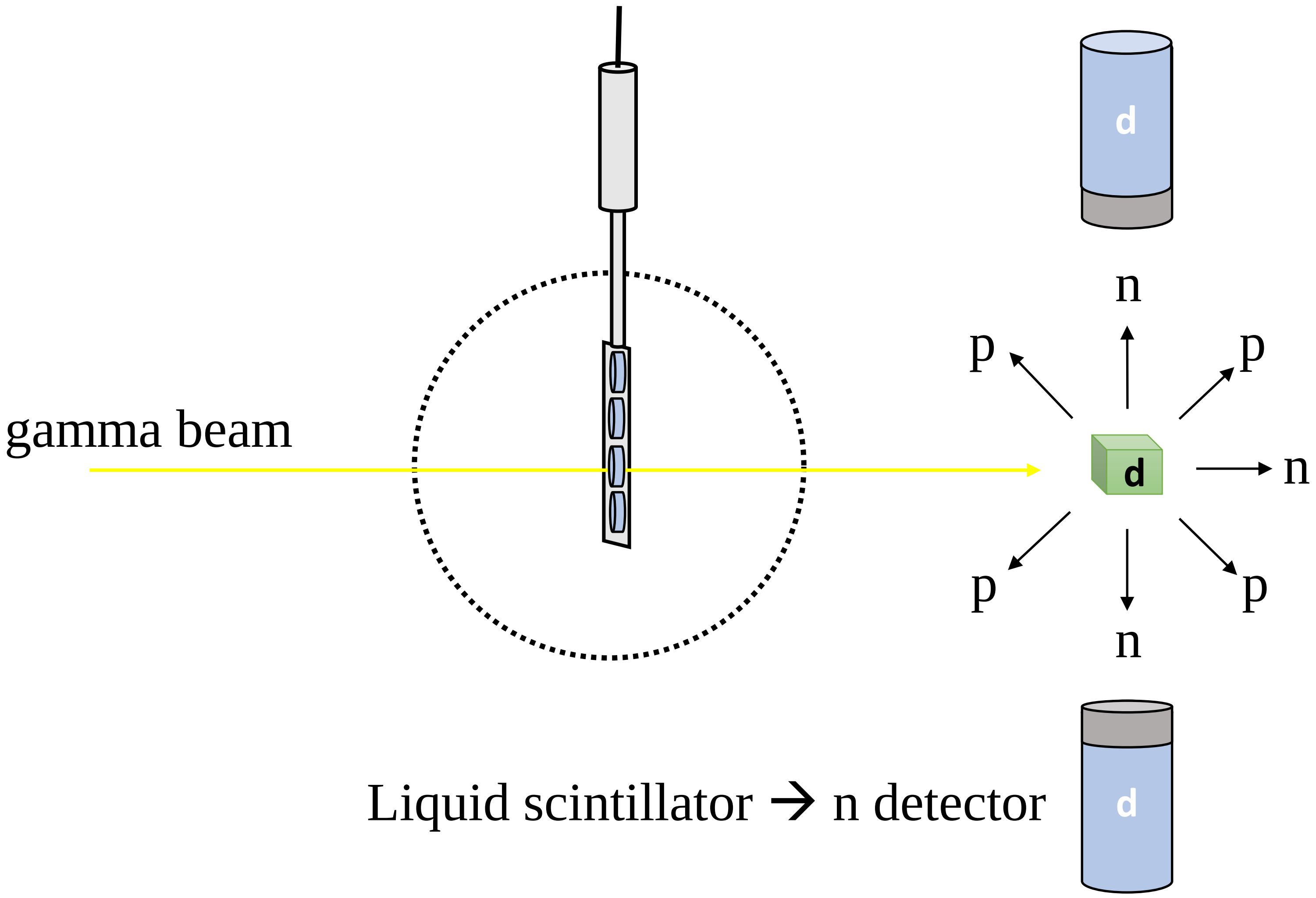


Pb glass intensity calibration

↓

Intensity measurement during the run

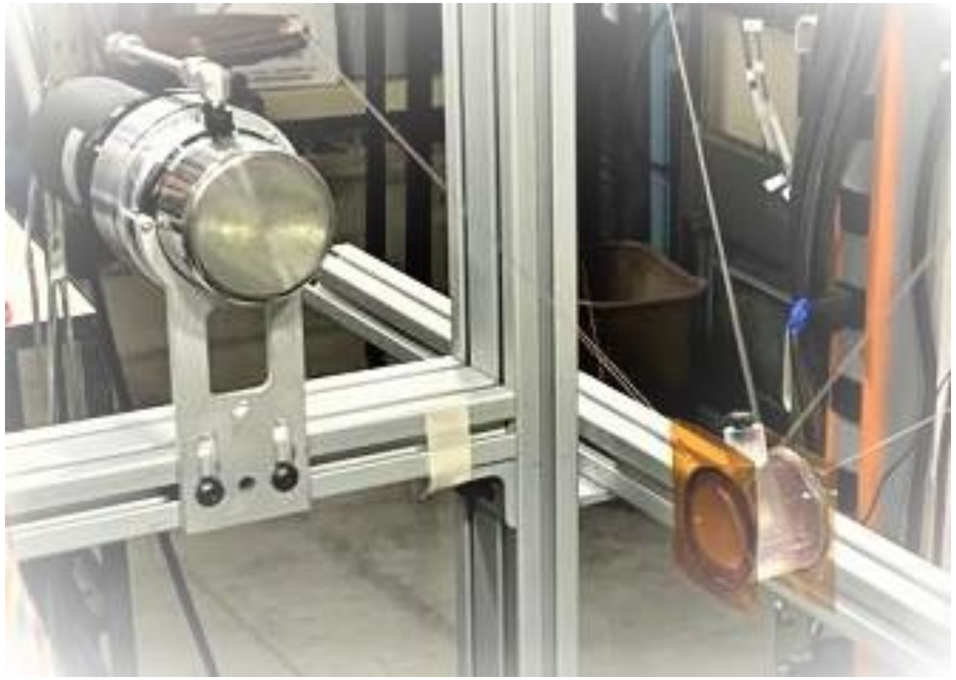
Gamma beam intensity measurement



Liquid scintillator → n detector

deuterium photodisintegration

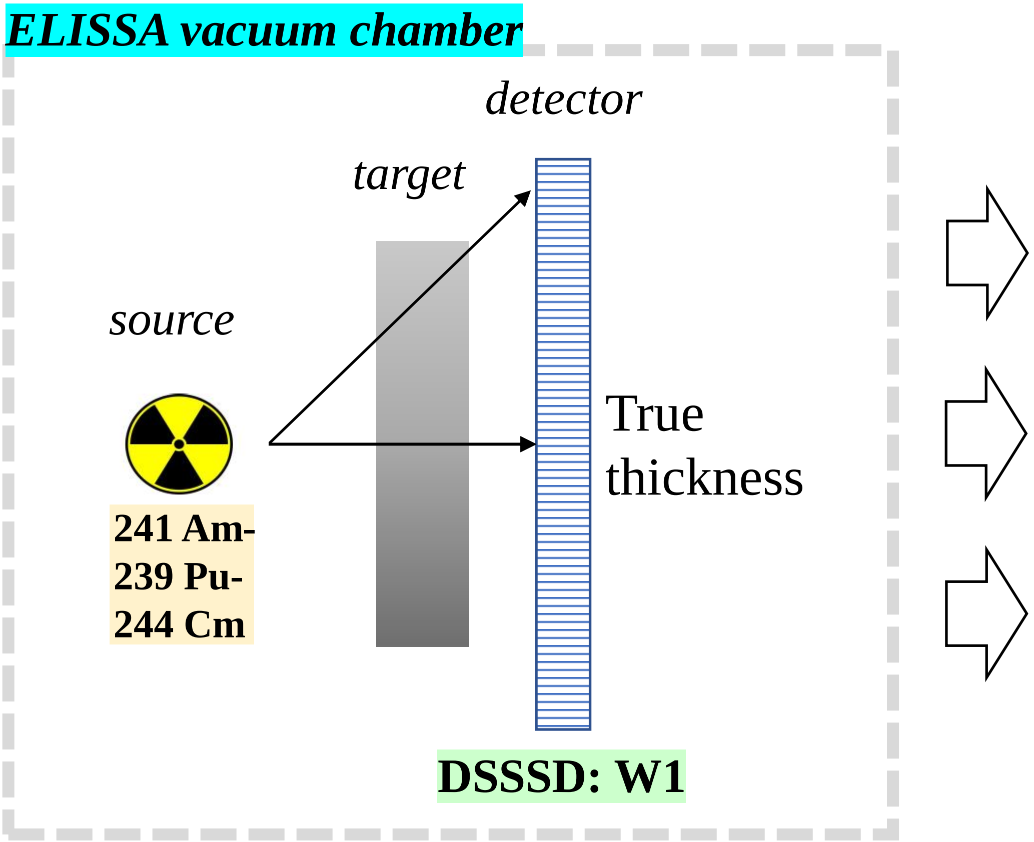
$$\boxed{d + \gamma = n + \mathrm{p} + 2.2\ \mathrm{MeV}}$$

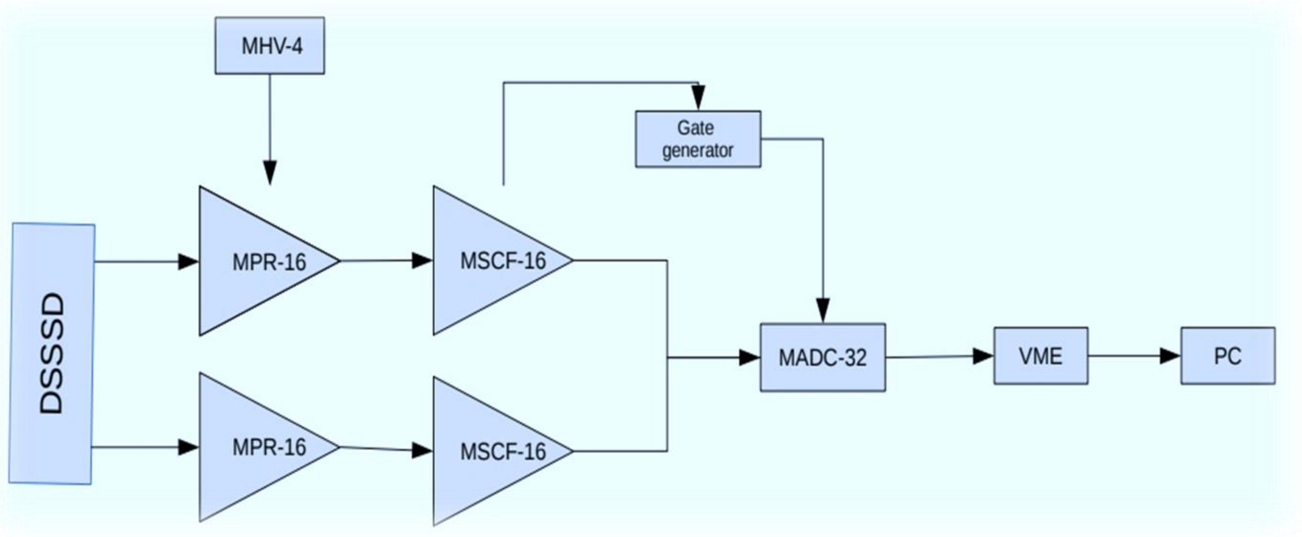


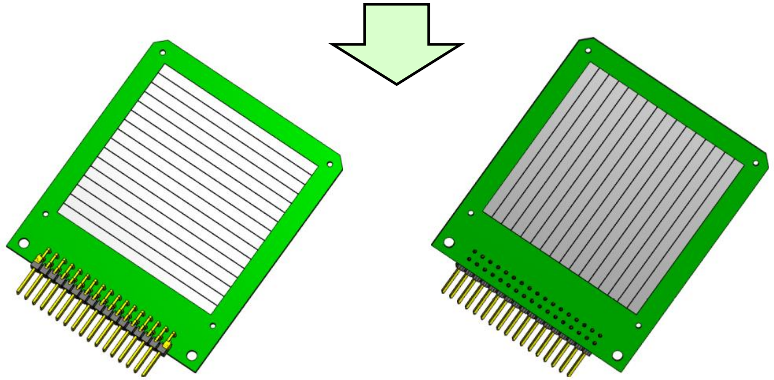
$$E_n = \frac{E_{gamma} - 2.2\ MeV}{2}$$

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

Target thickness measurement

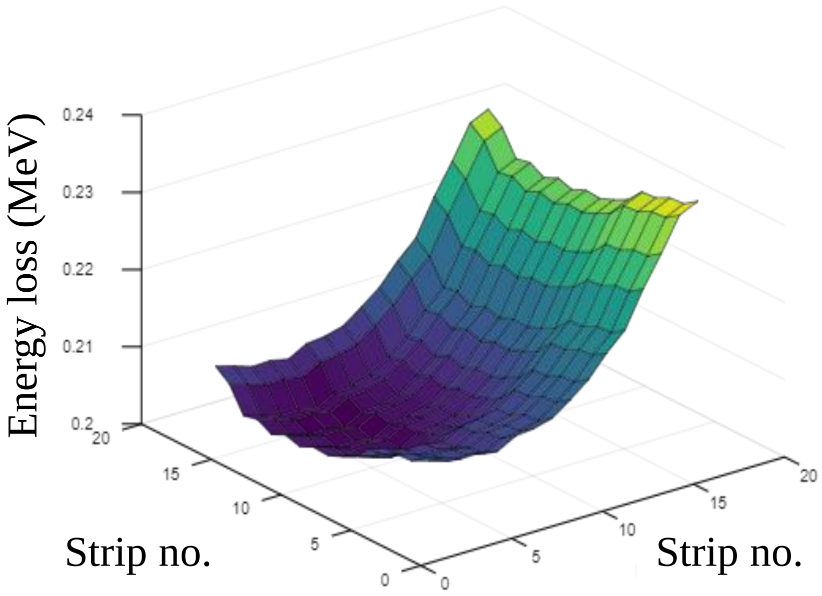


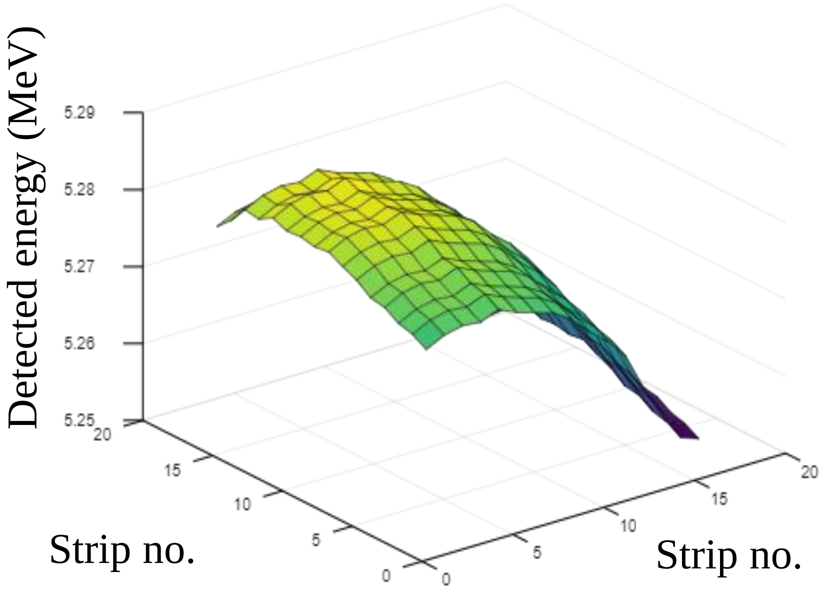




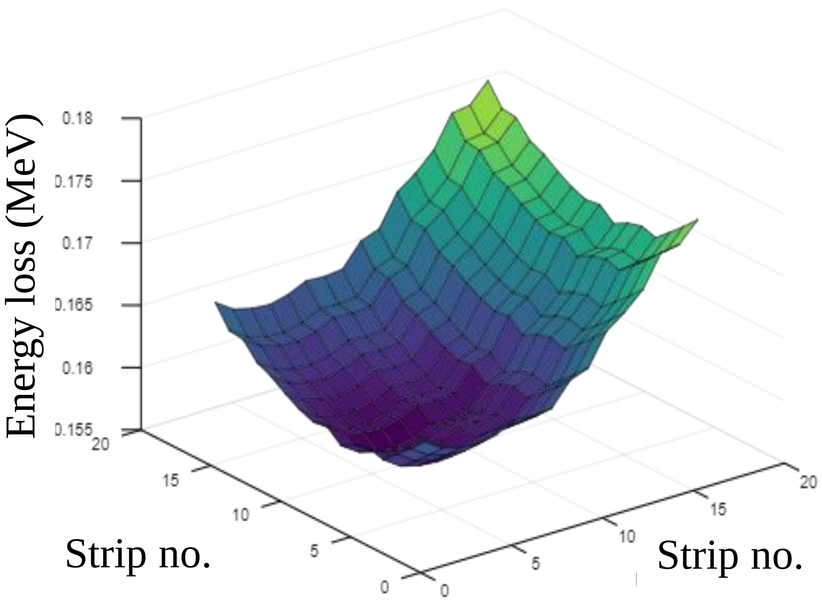
(a) Front side. (b) Rear side.

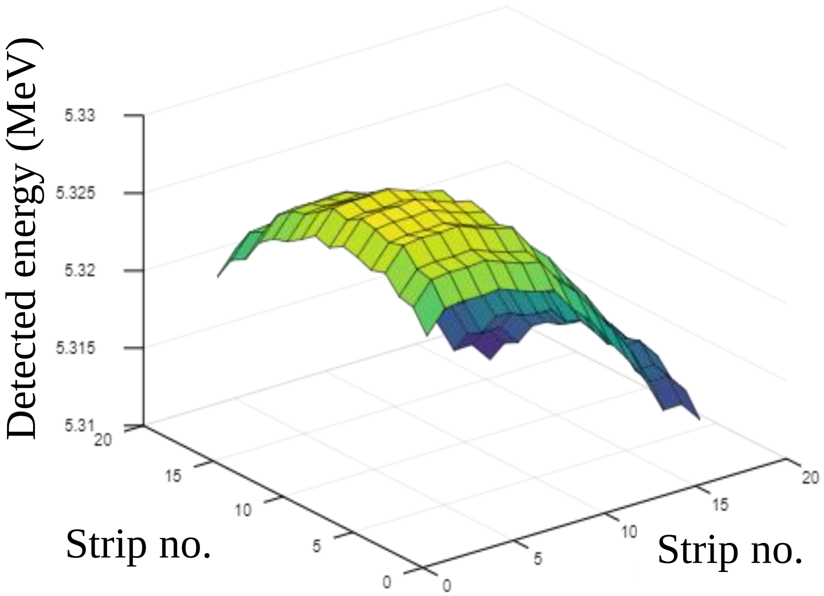
LiF #1



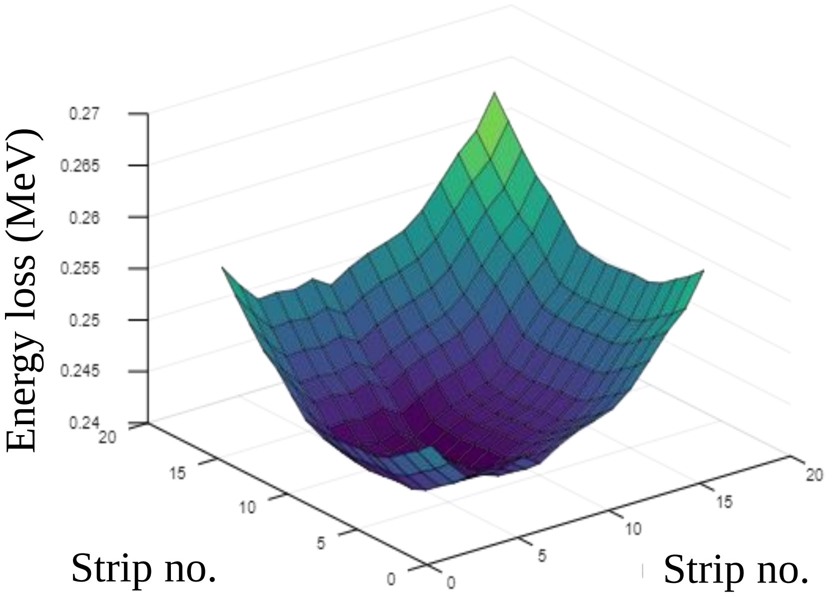


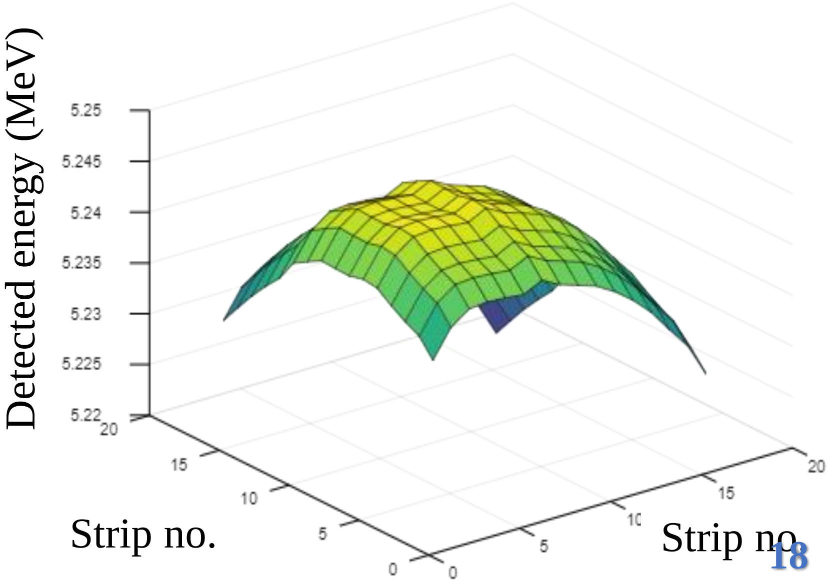
LiF #2





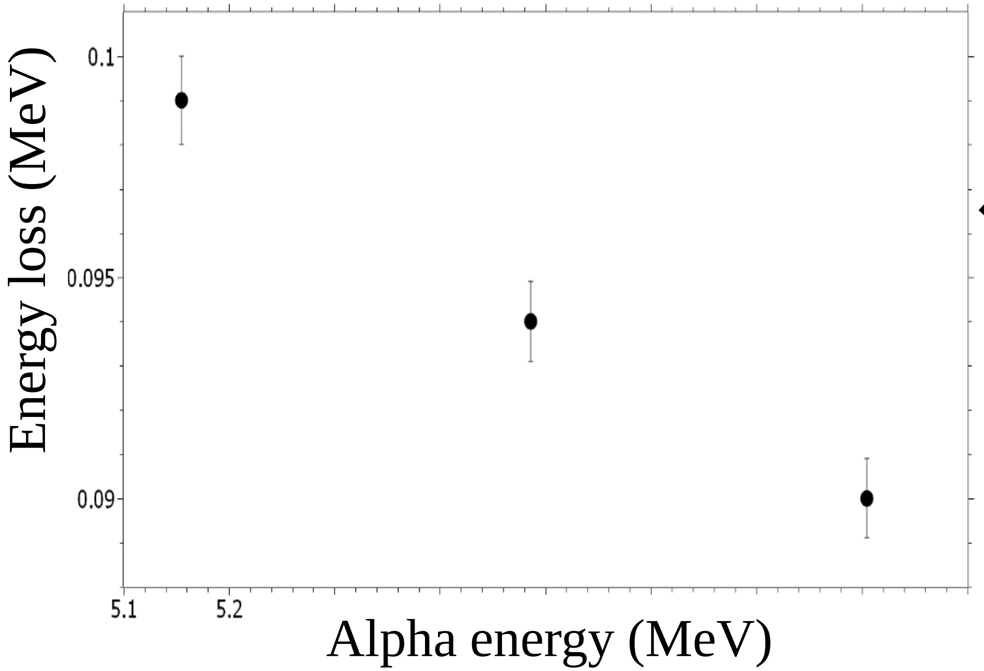
LiF #3





Results LiF #1

→ Substrate: Mylar (135 μg/cm^2)
→ Deposed material: LiF (expected 131 μg/cm^2)



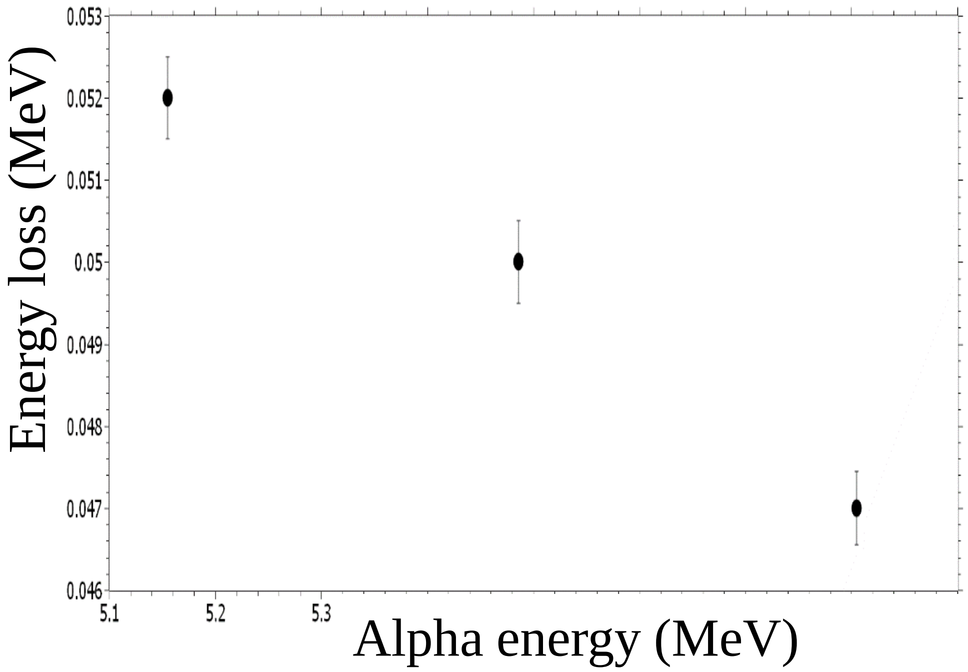
central values

Energy Loss (MeV)	Thickness (μm)	Thickness (μg/cm^2)
0.138 (+/-) 0.003	0.740 (+/-) 0.013	194.99 (+/-) 2.81
0.132 (+/-) 0.001	0.728 (+/-) 0.006	191.83 (+/-) 1.33
0.126 (+/-) 0.001	0.728 (+/-) 0.006	191.83 (+/-) 1.33

138,37 (+/-) 1.48 μg/cm^2

Results LiF #2

→ Substrate: Mylar (135 μg/cm^2)
→ Deposed material: LiF (expected 74 μg/cm^2)

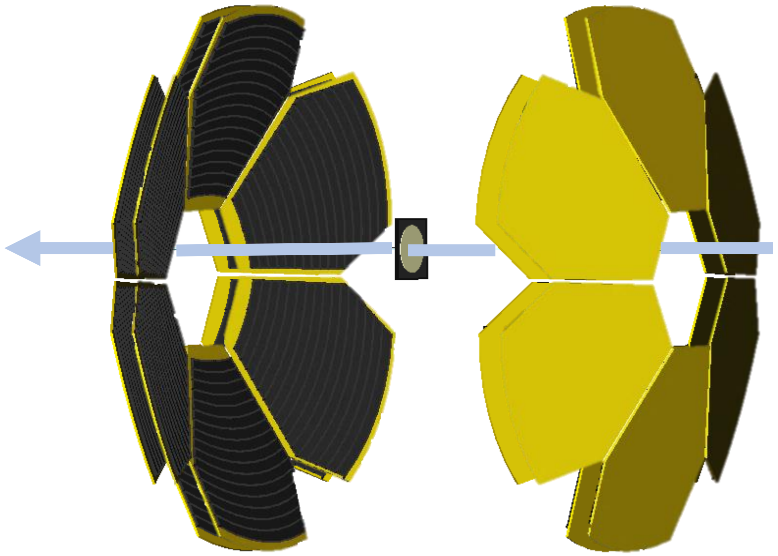


central values

Energy Loss (MeV)	Thickness (μm)	Thickness (μg/cm^2)
0.052 (+/-) 0.001	0.277 (+/-) 0.005	72.99 (+/-) 0.70
0.050 (+/-) 0.001	0.277 (+/-) 0.002	72.99 (+/-) 0.28
0.047 (+/-) 0.001	0.277 (+/-) 0.002	72.99 (+/-) 0.28

72.99 (+/-) 0.42 μg/cm^2

p – process

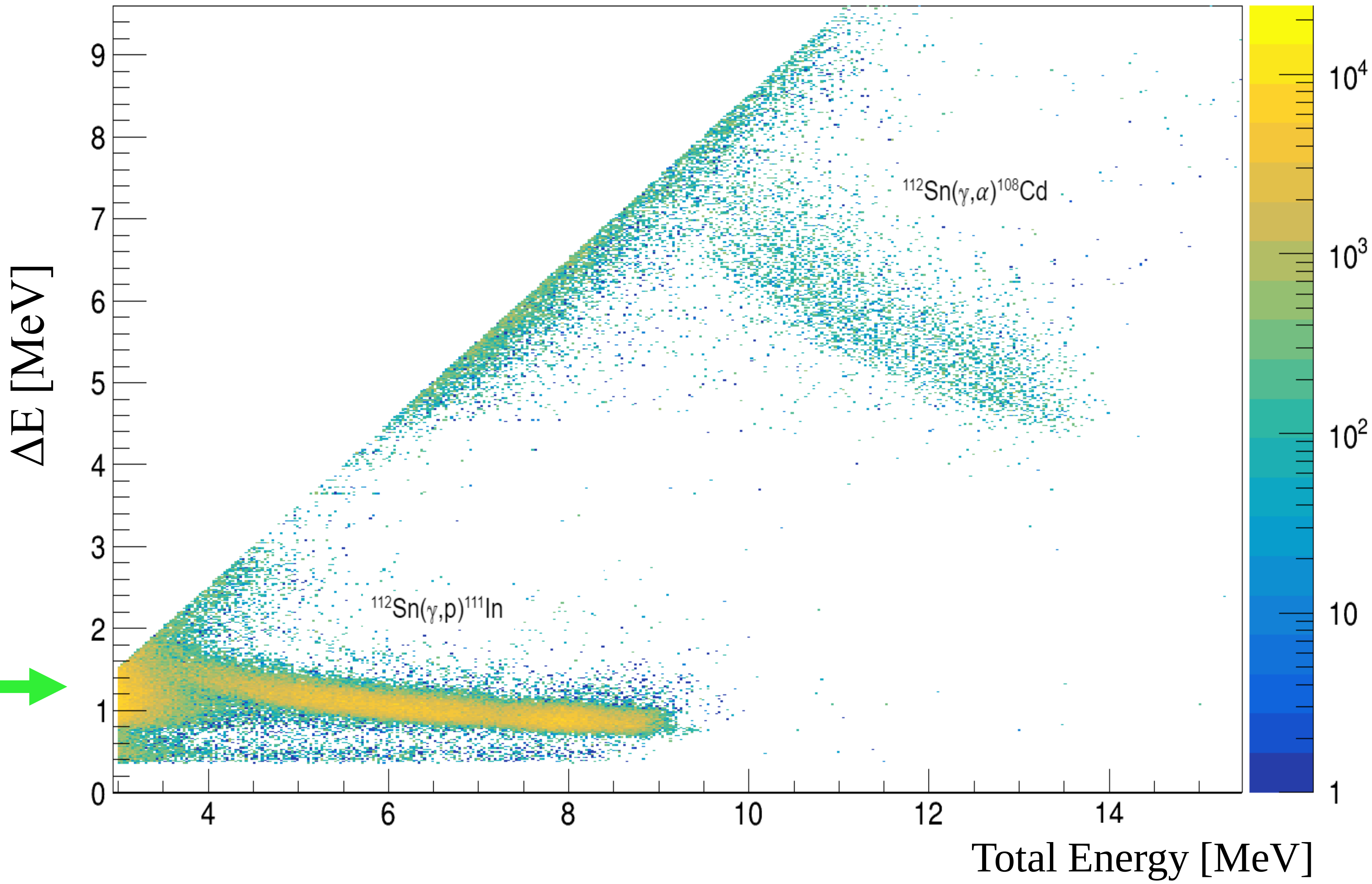


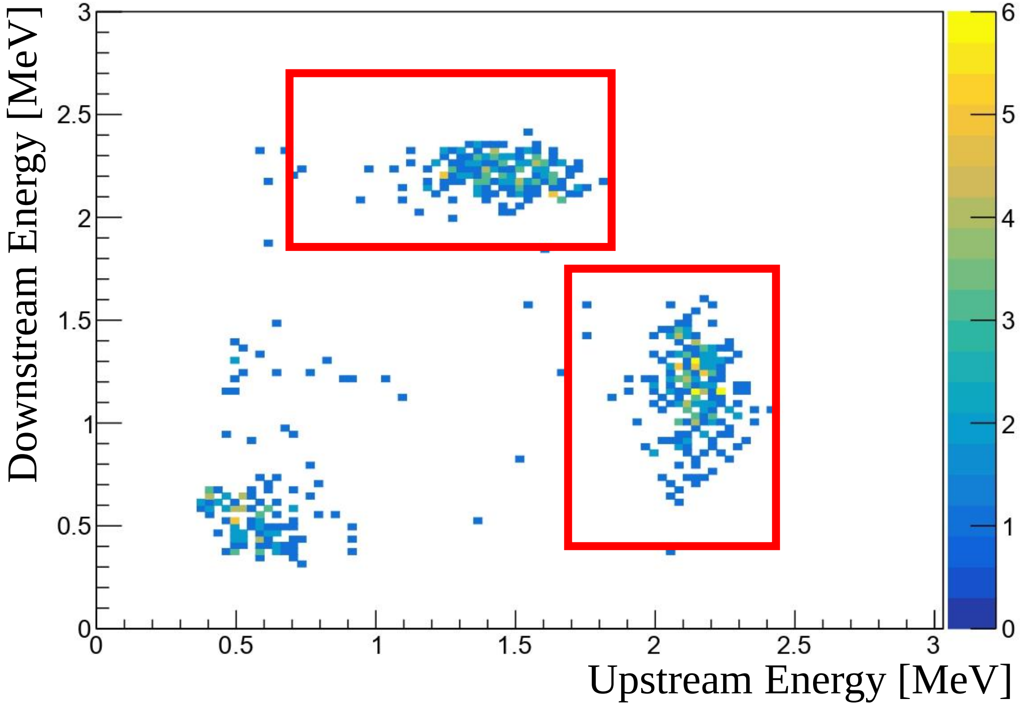
$$^{102}Pd(\gamma,p)^{101}Rh$$

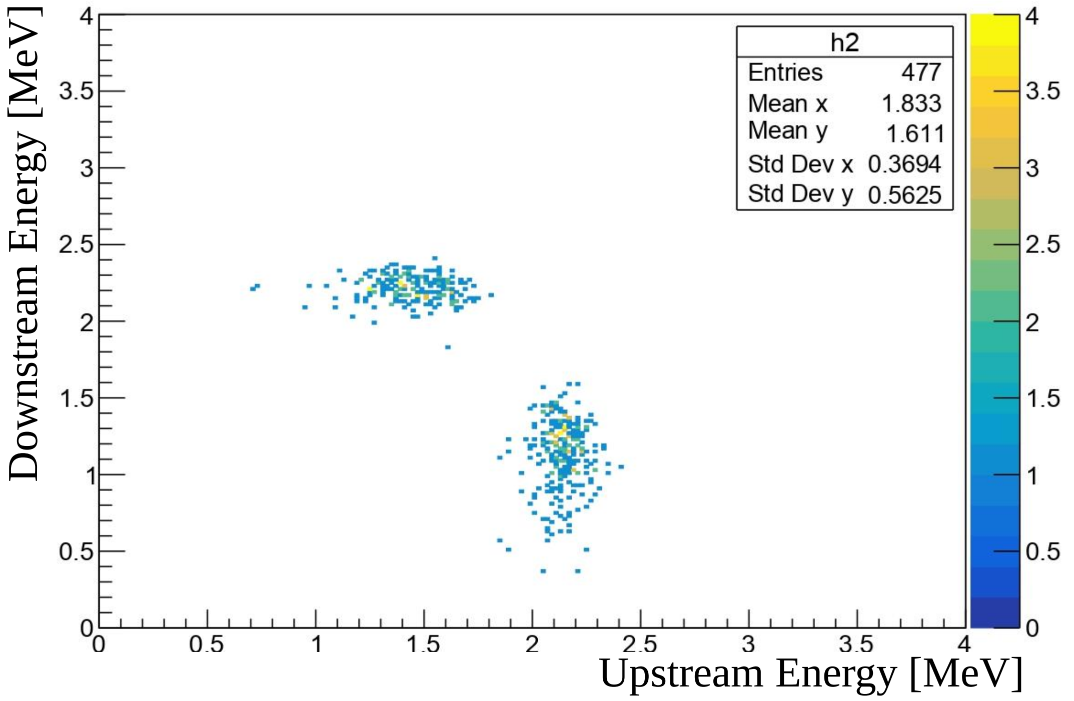
$$^{102}Pd(\gamma,\alpha)^{98}Ru$$

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

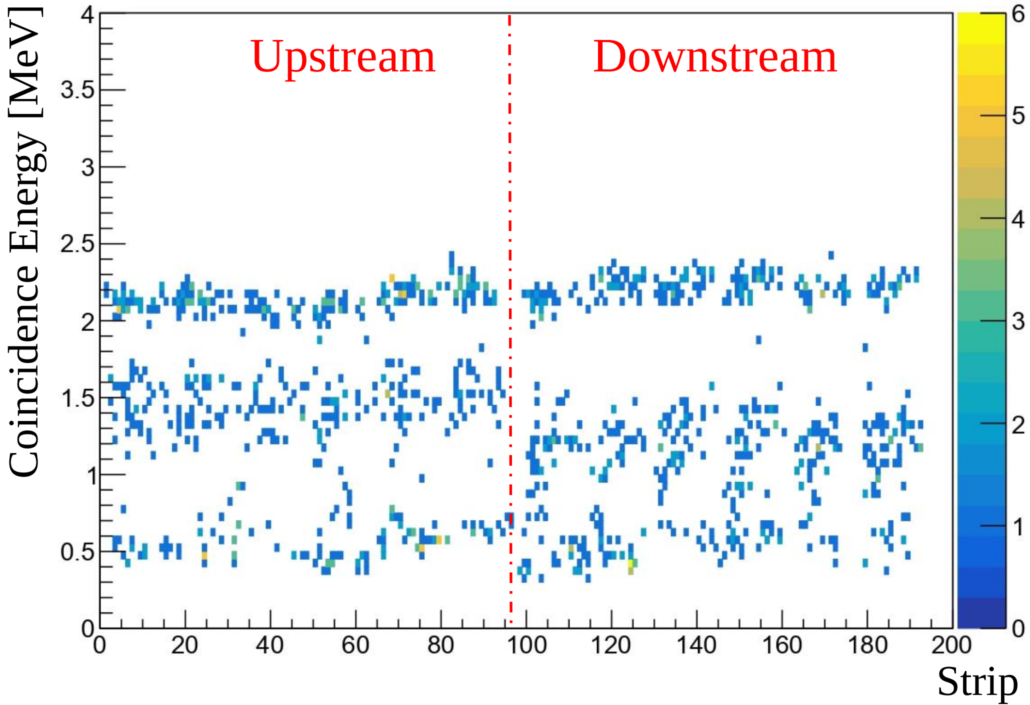
$$^{112}Sn(\gamma,\alpha)^{108}Cd$$

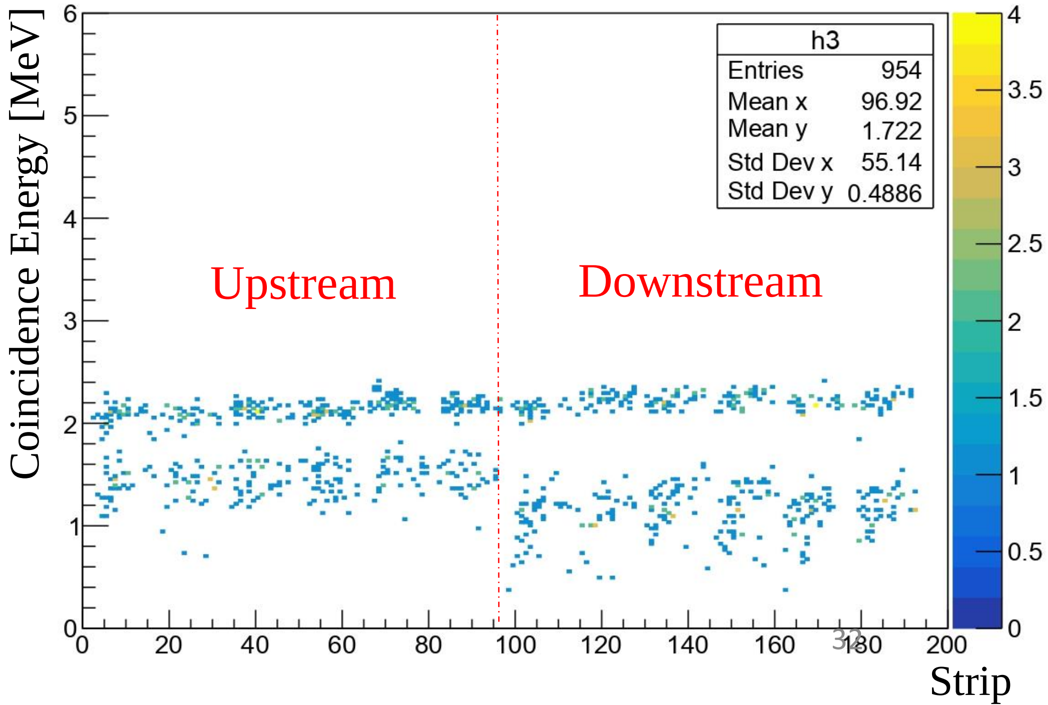


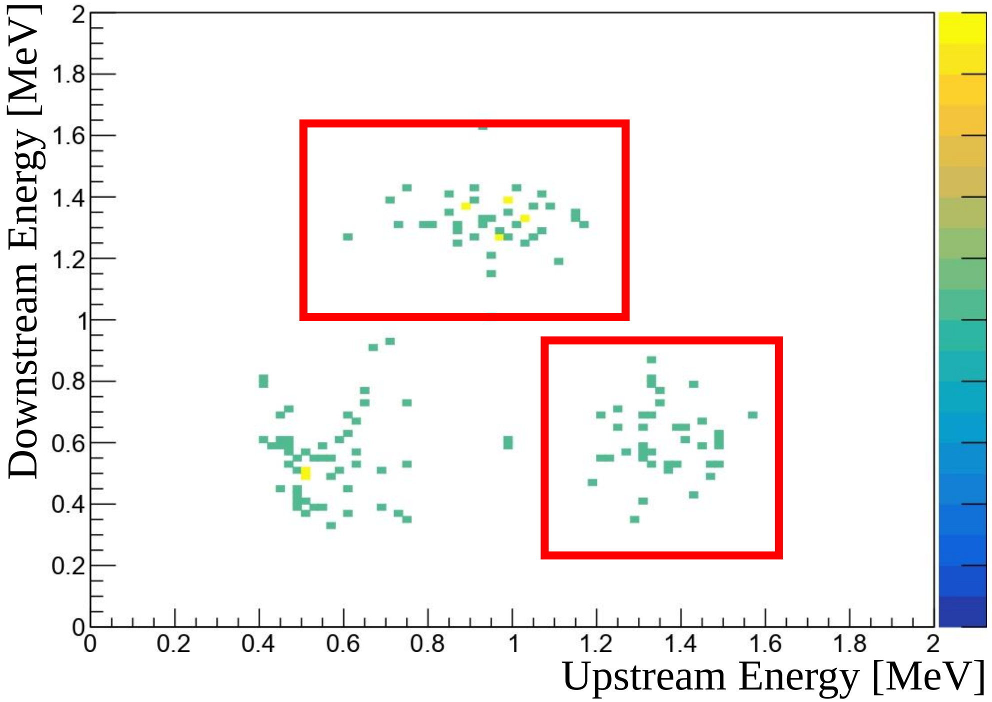


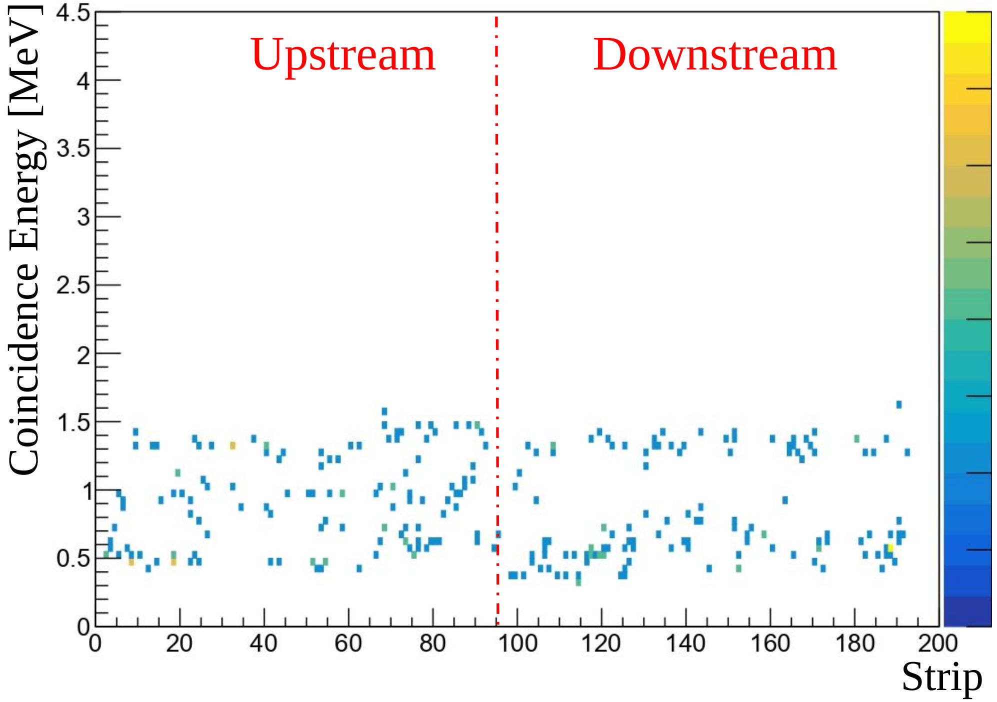


Background can be easily subtracted for **6 MeV**

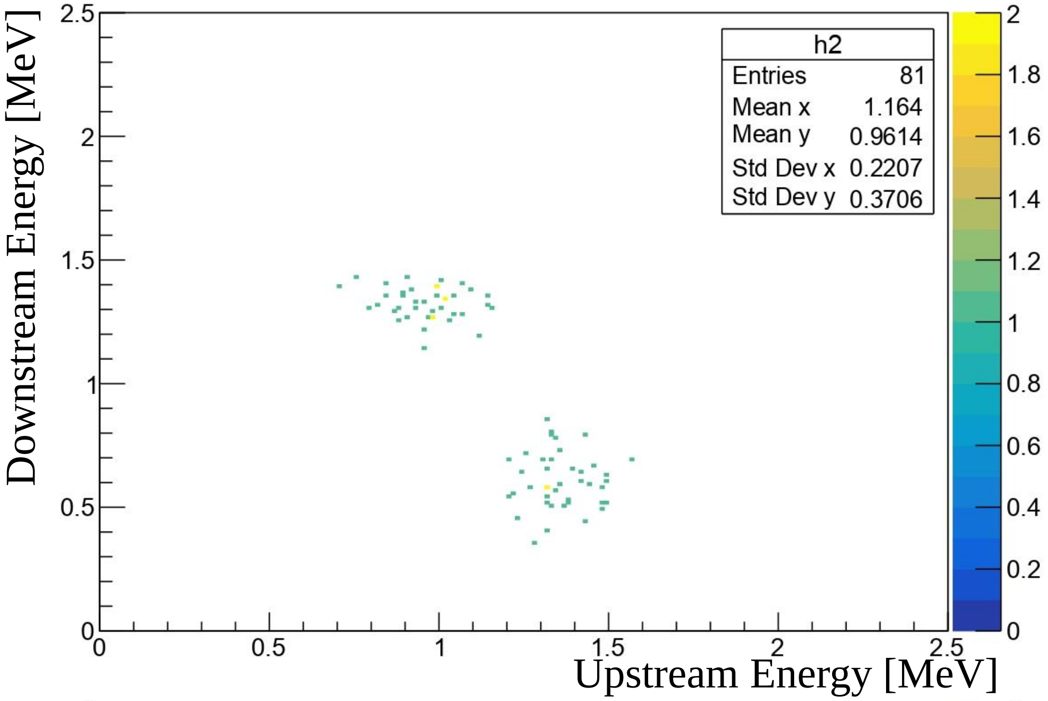


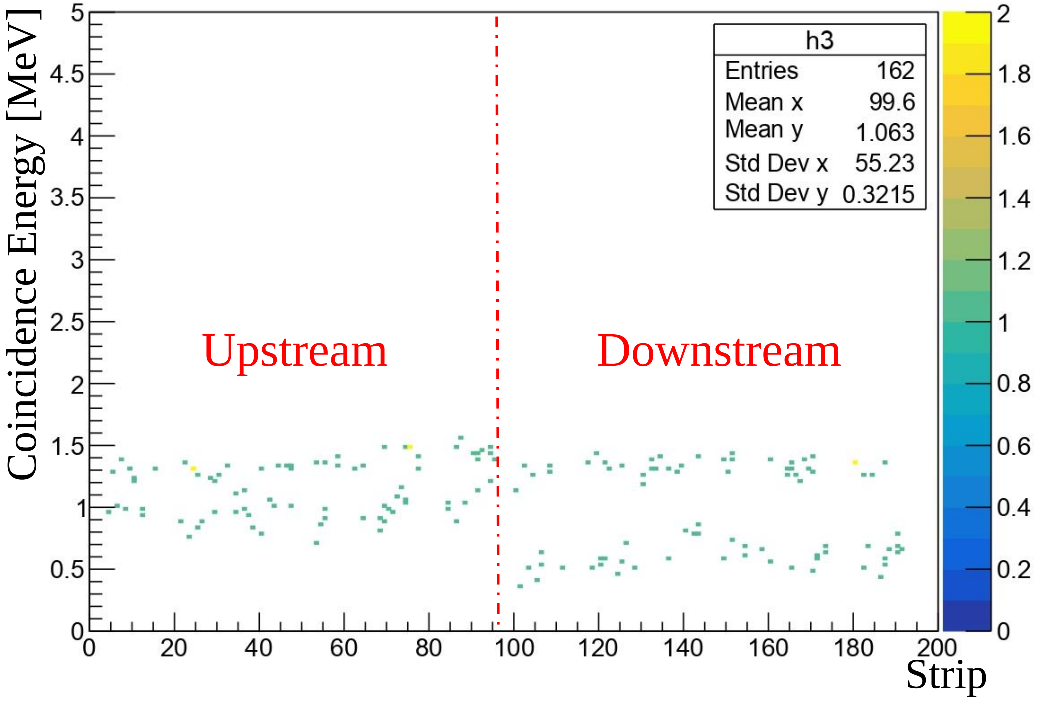


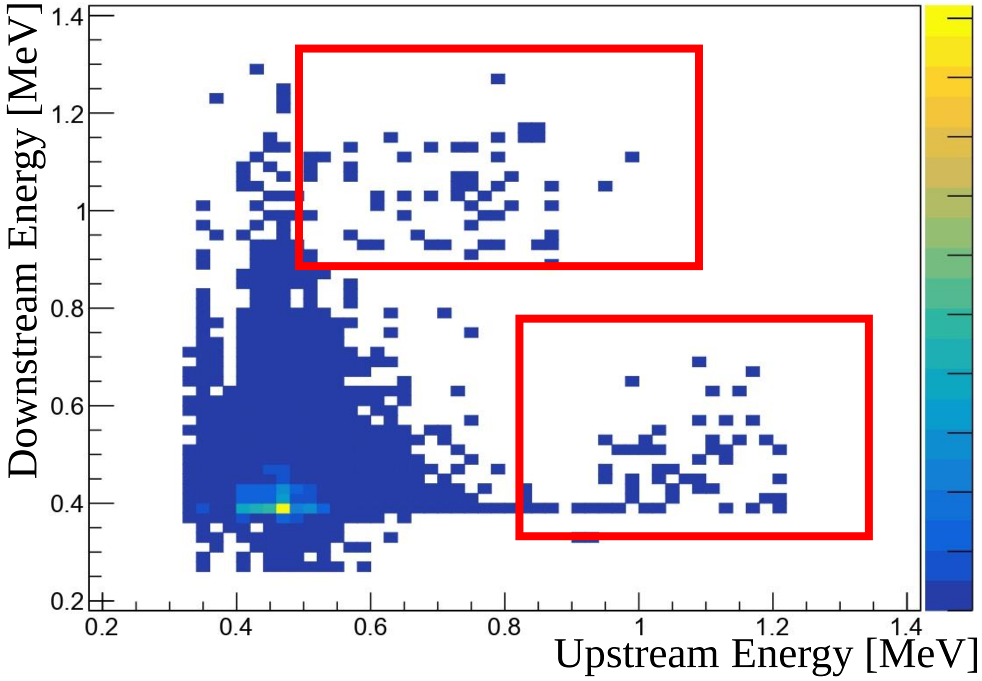


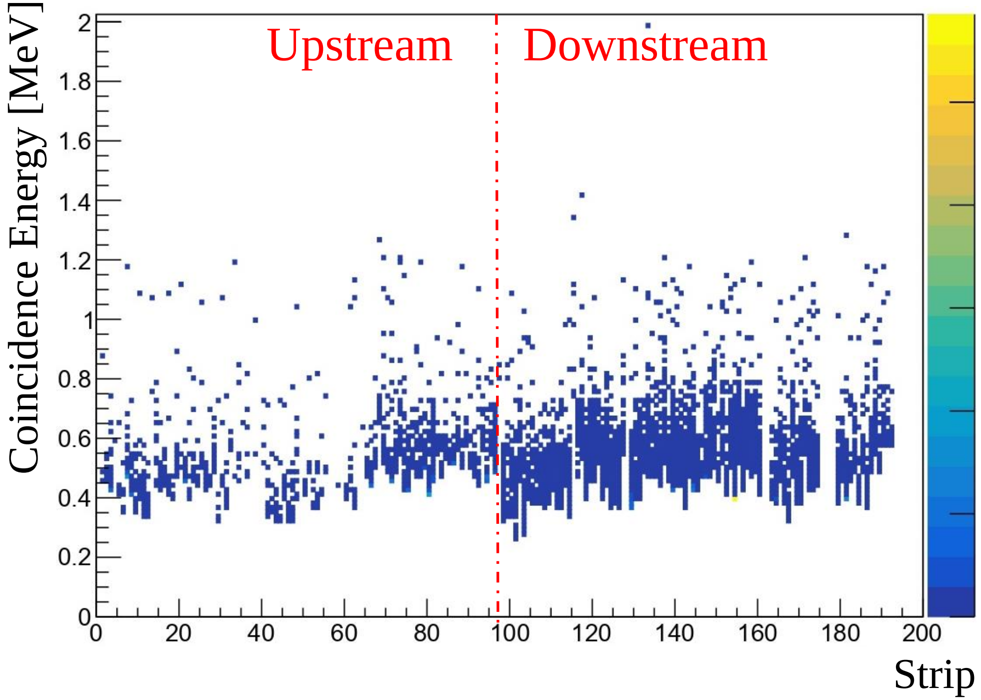


And even for **4.5 MeV**

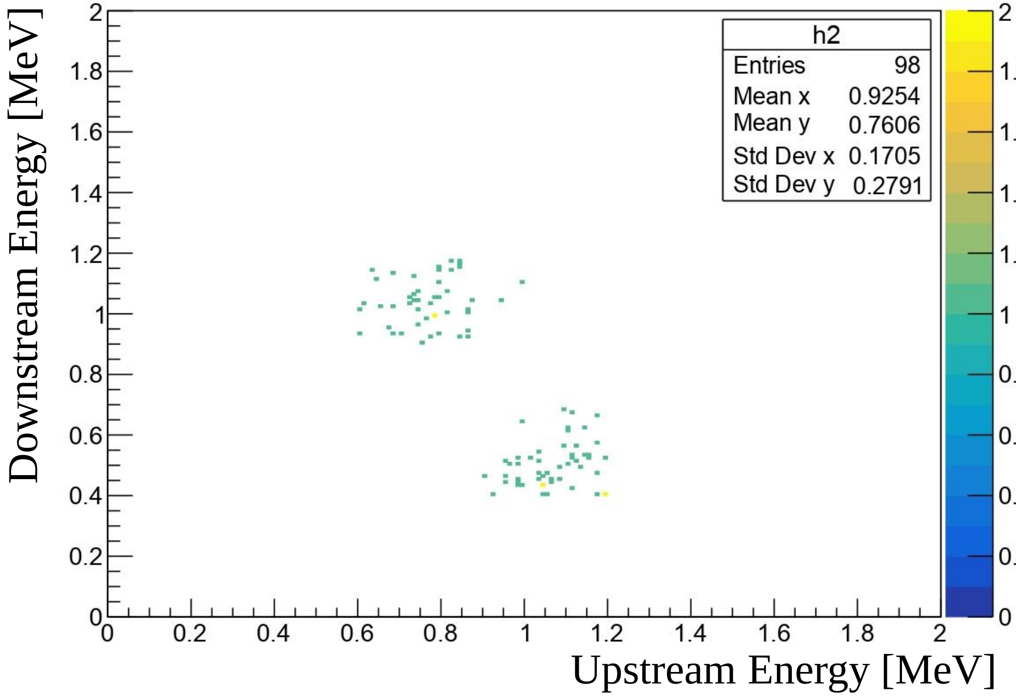


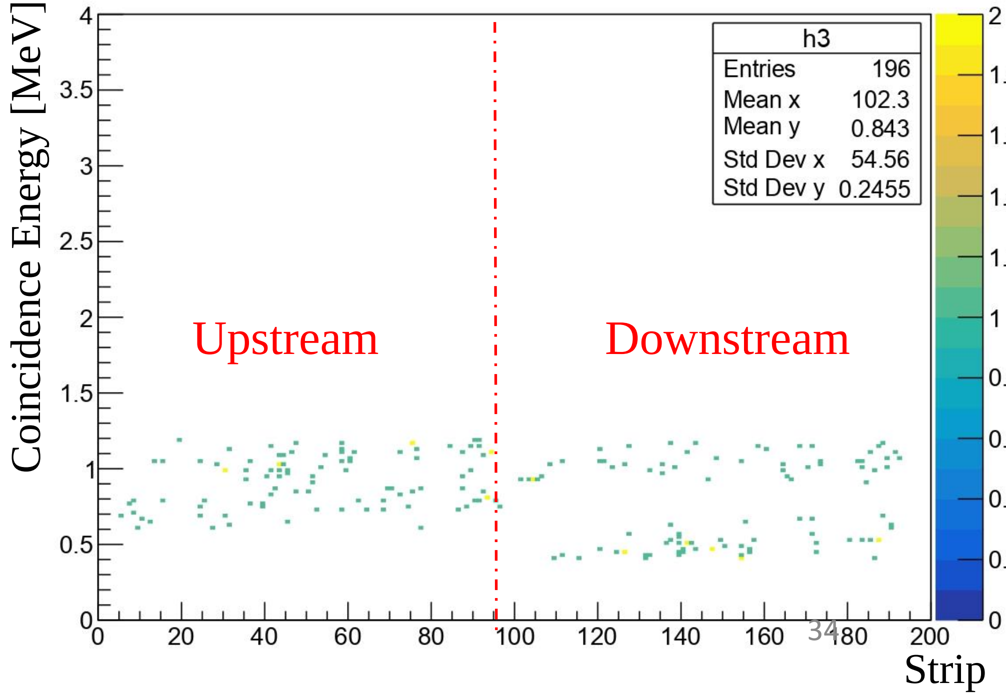


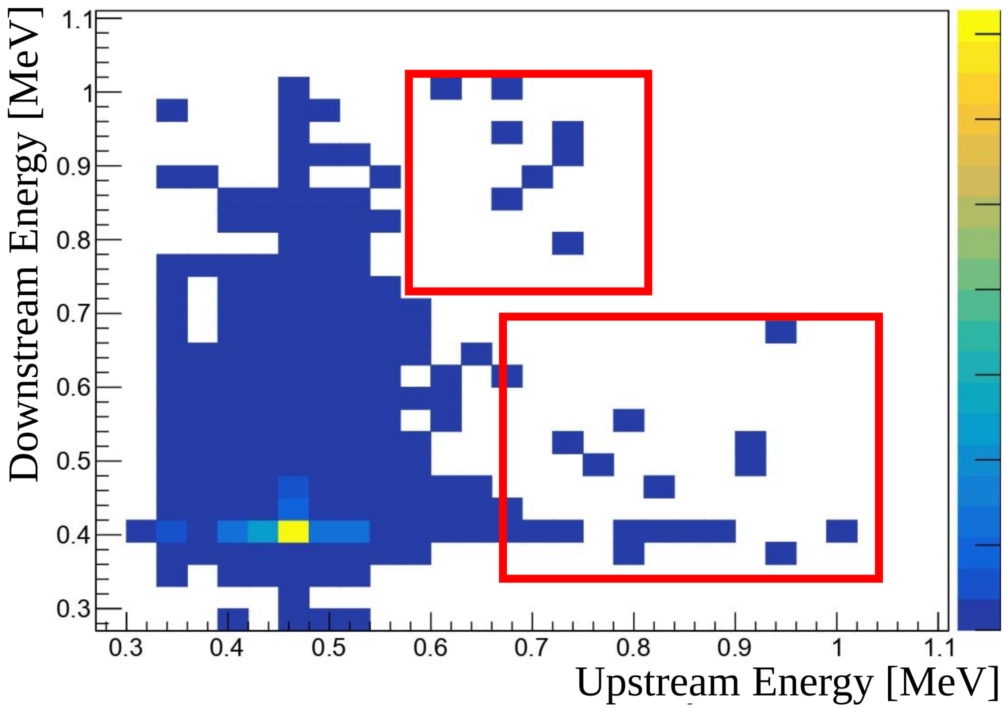


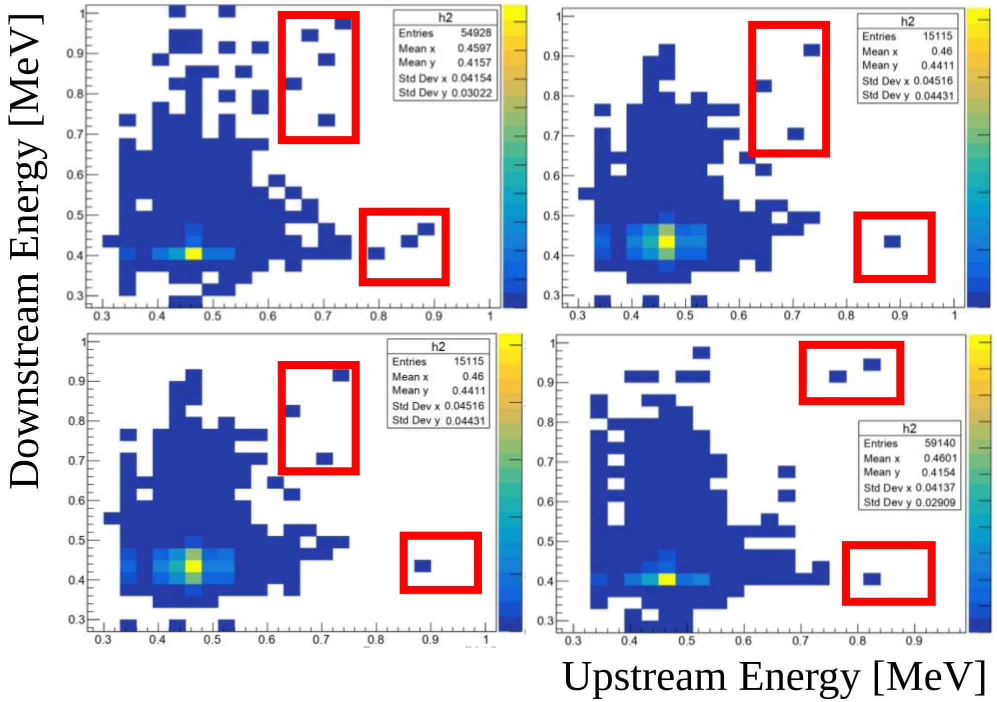


Still possible for **4 MeV**









Difficult to distinguish for **3.7 MeV**