Nuclear fragmentation in particle therapy and space radiation protection: from the standard approach to the FOOT experiment

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- Simple, flexible, cheaper setup
- Beam fragments only

- Different experimental strategies
- Mooore complex setup
- More information about fragments

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- Secondary neutrons production by a 1 GeV/u ^{58}Ni ions beam in target relevant for space applications

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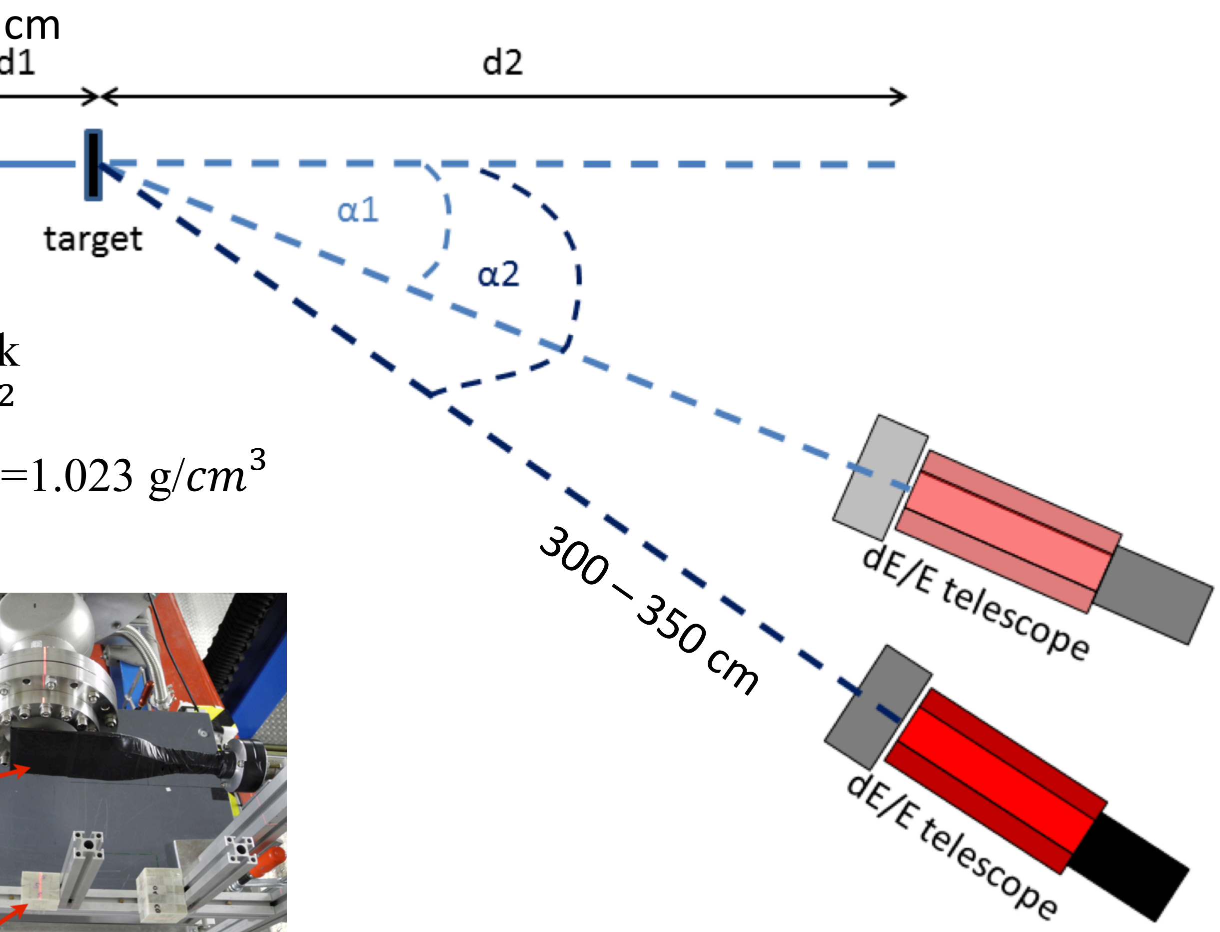
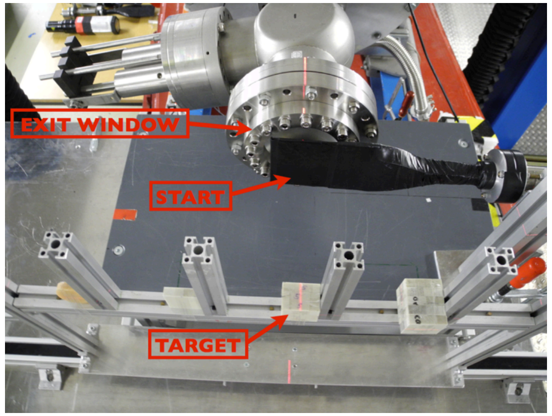
- Fragments identification
- Cross sections machinery
- Performances study
- Real data analysis
- Future work with neutrons

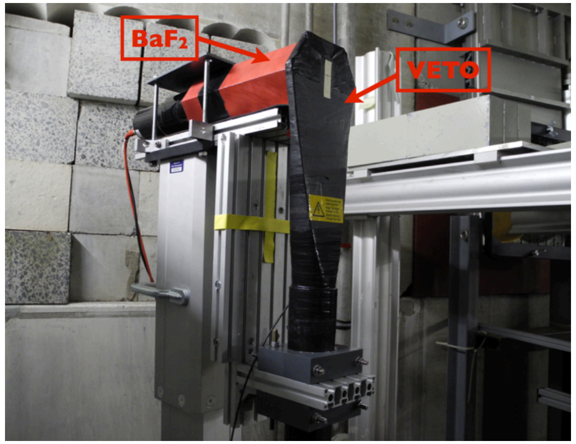
Standard experimental setup

GSI, Cave A (Experimental cave)



START
- 2 mm thick
- 10x10 cm^2
- BC400 , ρ=1.023 g/cm^3





dE - VETO
- 9 mm thick
- Exagonally shaped, 5.4 cm radius
- BC400 , ρ=1.023 g/cm^3

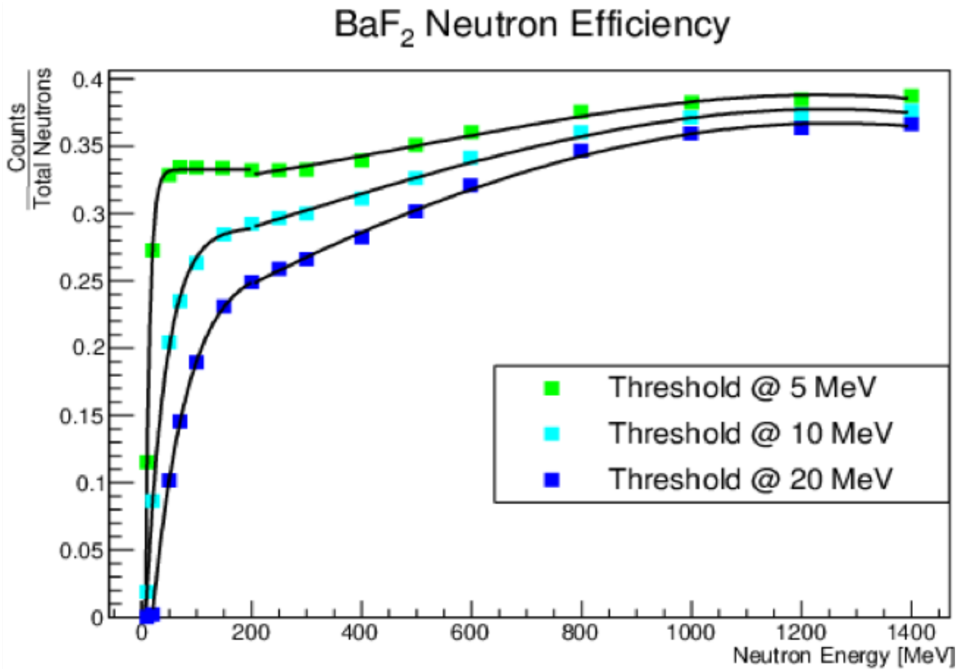
E - BaF_2
- 14 cm lenght
- Exagonally shaped, 4.5 cm radius
- ρ=4.88 g/cm^3

BaF_2 efficiency to neutrons

- GEANT4 simulation
- Monoenergetic neutrons with kinetic energies spanning between 10 MeV and 1400 MeV

$$\varepsilon_{BaF_2} = \frac{N_p(E_{kin})}{N_n(E_{kin})}$$

N_p = particles detected by the crystal
N_n = incident neutrons
E_{kin} = kinetic energy of incident neutrons

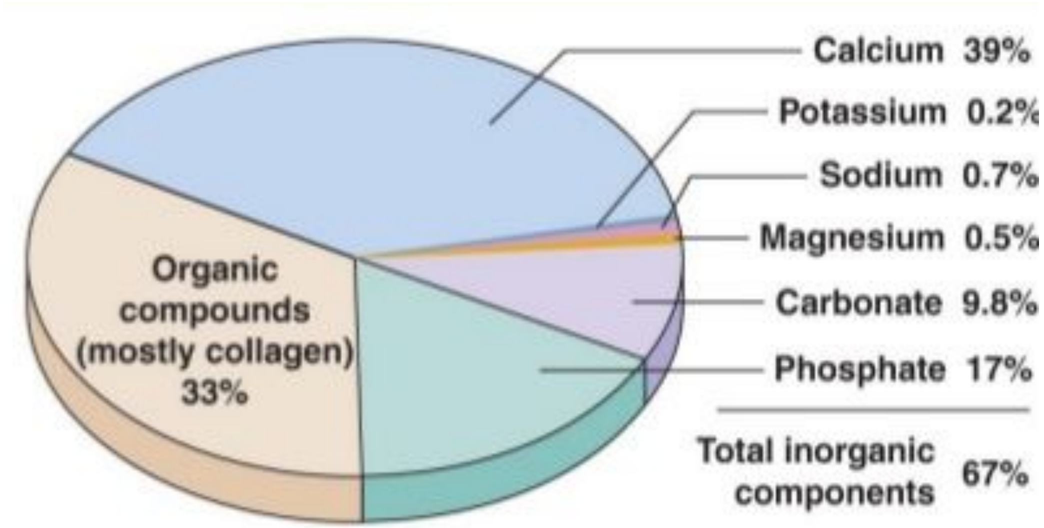


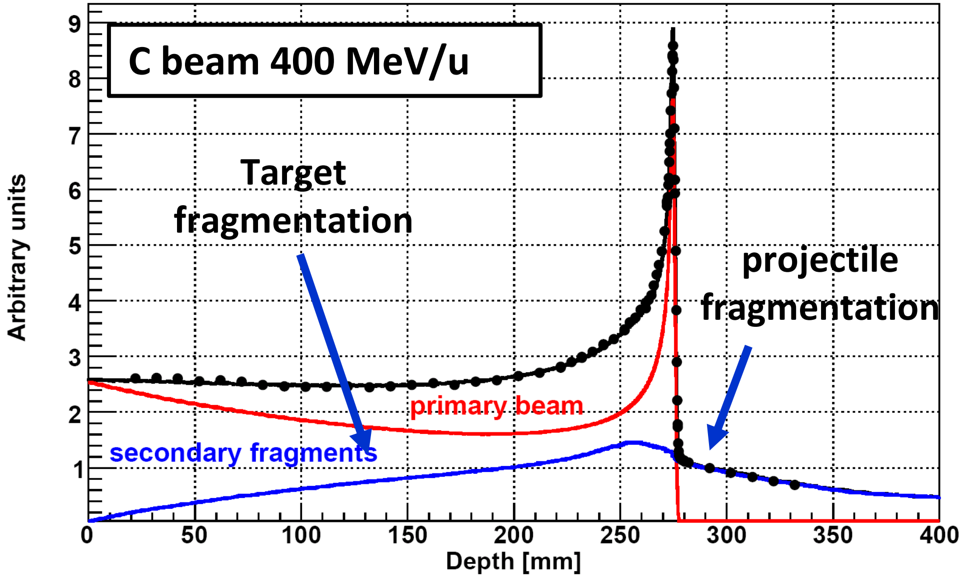
$$f_1(x) = a_0 + a_1 x \qquad x < 200\ MeV$$
$$f_2(x) = b_0 + b_1 x + b_2 x^2 + b_3 x^3 \qquad x > 200\ MeV$$

Applied to the offline analysis

Bone-like materials

Composition of bone





Beam: 400 MeV/u ^{12}C

Target: 5 cm compact bone simulant

% by weight	H	C	N	O	Ca	Cl
	3.10	31.26	0.99	37.57	27.03	0.05

Goal

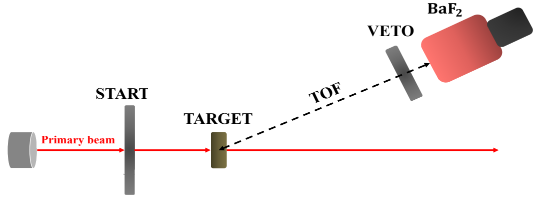
Characterization of secondary fragments pruduced in 5cm compact-bone target at 2, 4, 6, 7, 10, 30 deg wrt the primary beam direction

The ROSSINI collaboration

Radiation shielding by ISRU and innovative materials for EVA, vehicles and habitats

Beam: 1 GeV/u ^{58}Ni

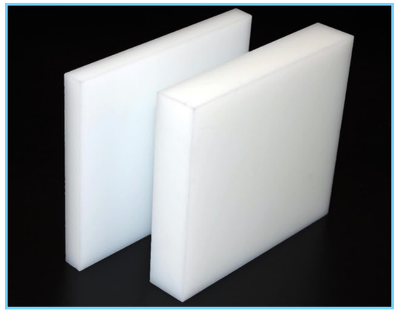
$\Delta E/E$ system placed at 24 deg



Target:

Space journey

Polyethylene



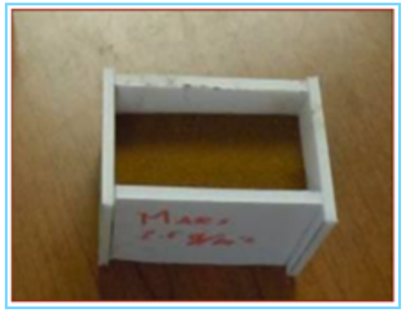
Aluminum

Surface habitation

Lunar regolith

Lunar concrete

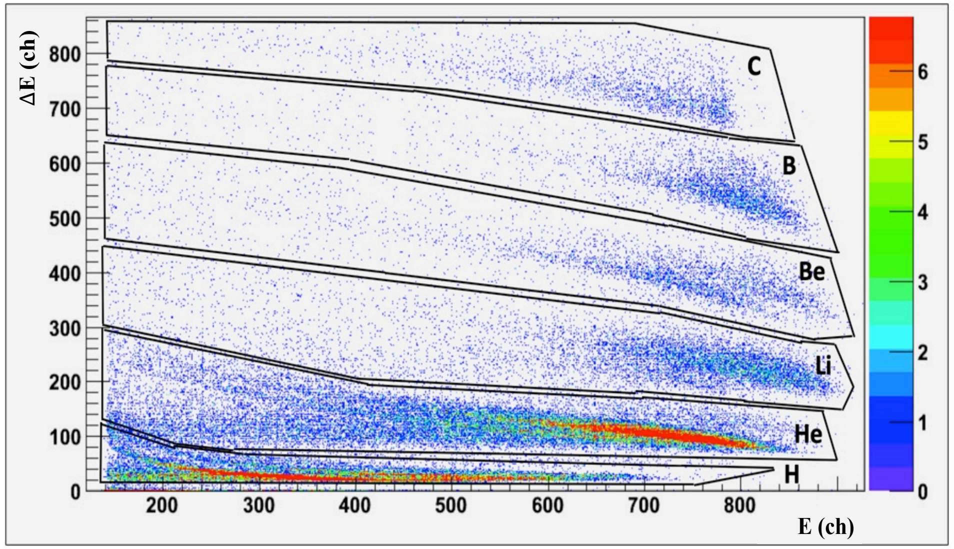
Mars regolith

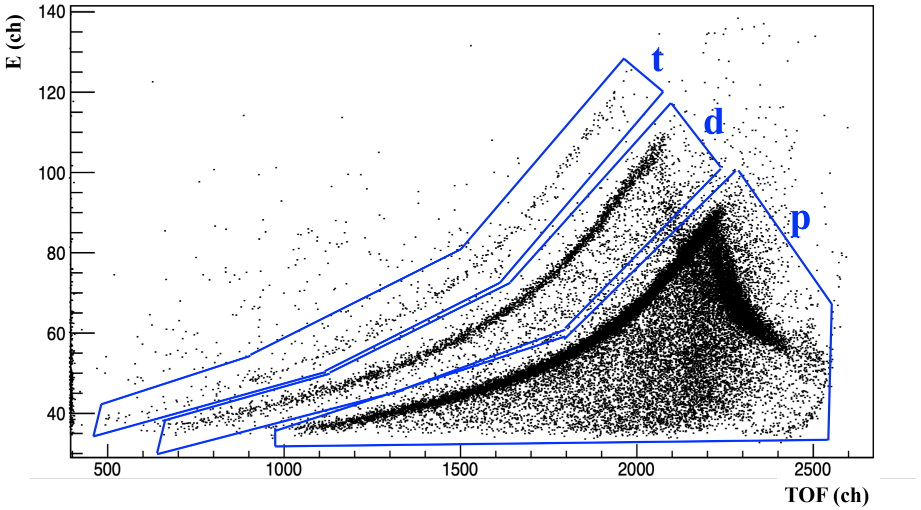


Goal

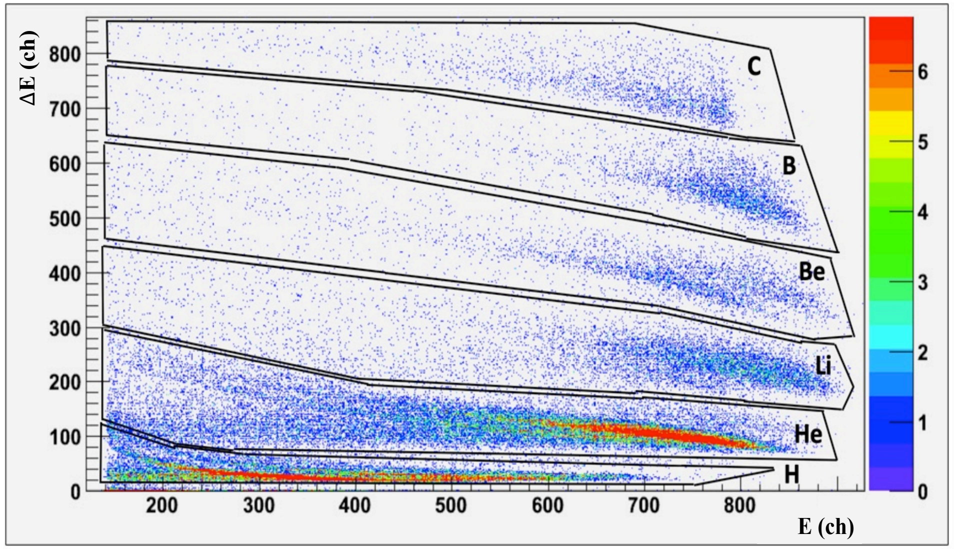
Characterization of secondary neutrons production in several targets in order to test new shielding materials

Particle identification

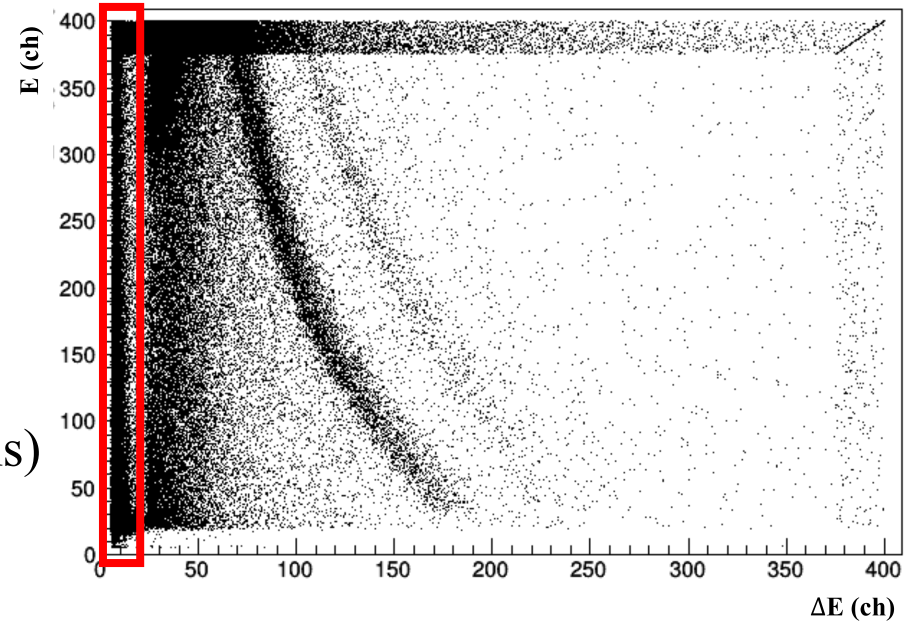


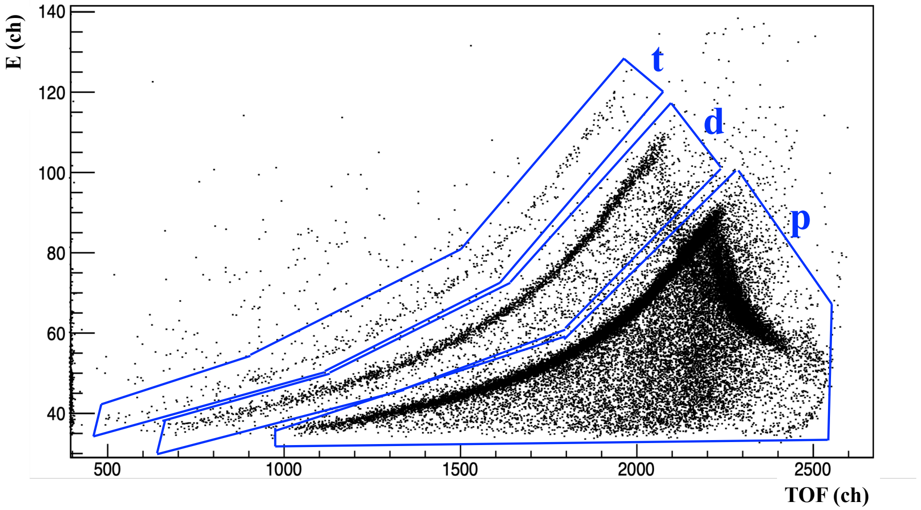


Particle identification

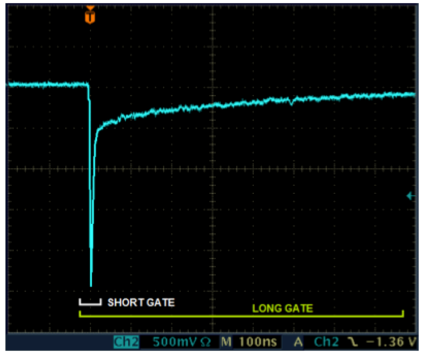


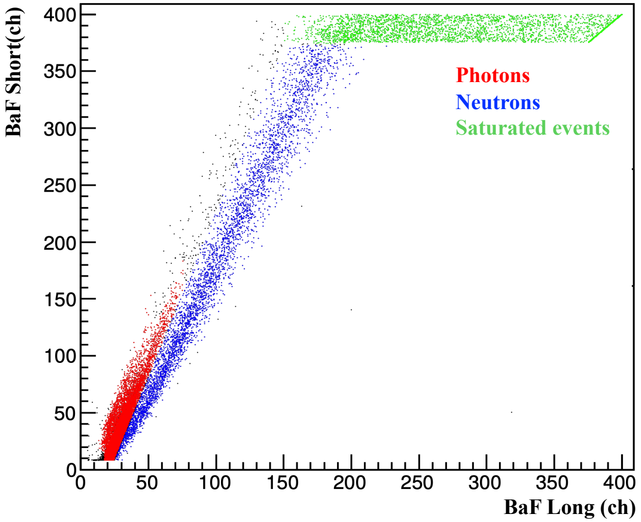
Neutral particles
(neutrons + photons)





BaF_2 components lenght
Short: 54 ns
Long: 800 ns



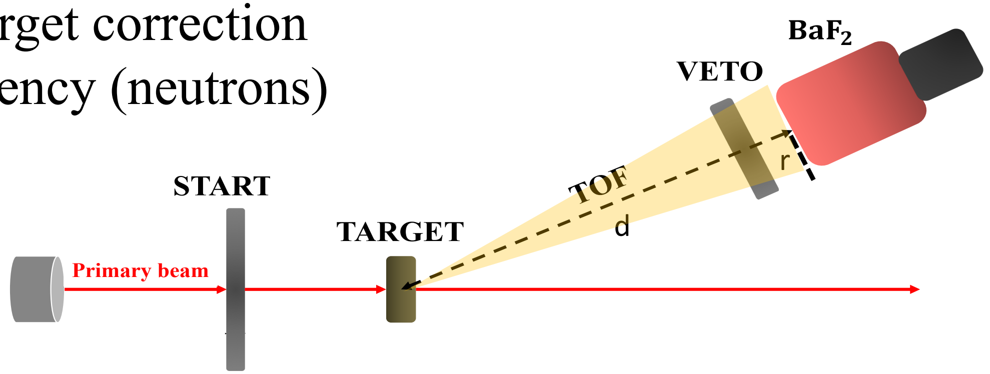


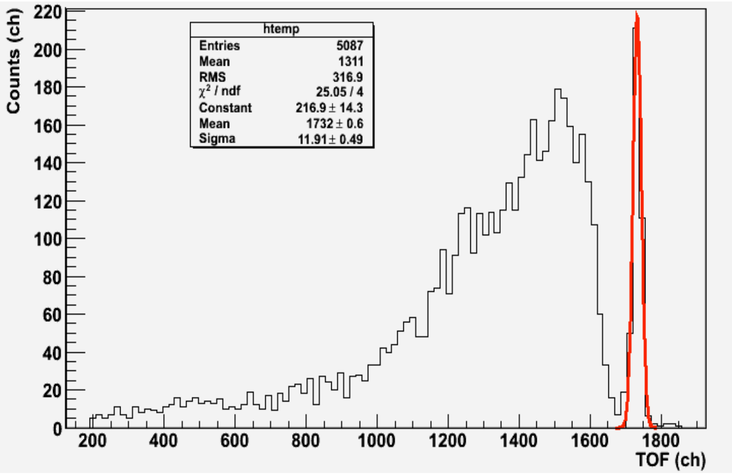
Particle identification

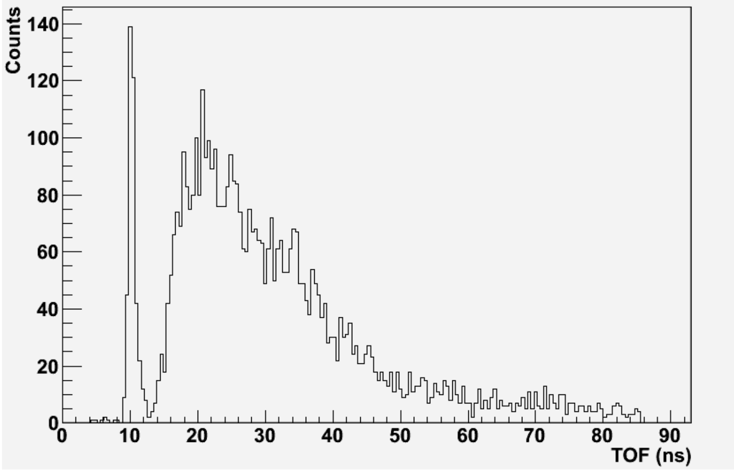
$$\text{Yield} = \frac{\text{Counts corrected (Z, A)}}{N_{\text{primaries}}\,\Omega}$$

- Dead time correction
- No-target correction
- Efficiency (neutrons)

$$\Omega = \frac{\pi r^2}{d^2}$$





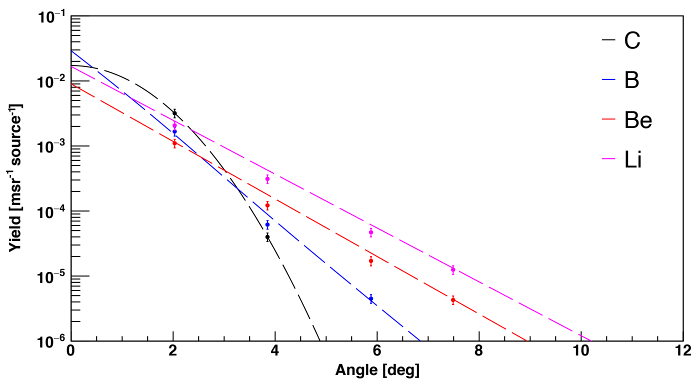


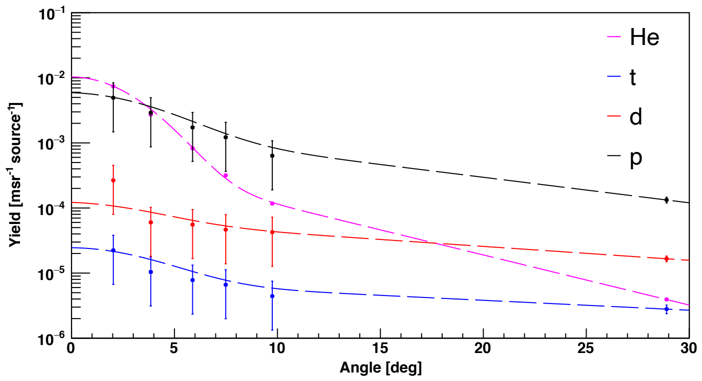
$$E_{kin} = \left(\frac{1}{\sqrt{1-\left(\frac{d}{\text{TOF}\cdot c^2}\right)}} - 1\right) m_0 c^2$$

Gaussian fit applied to the photons peak in order to estimate its position and sigma

Compact bone data

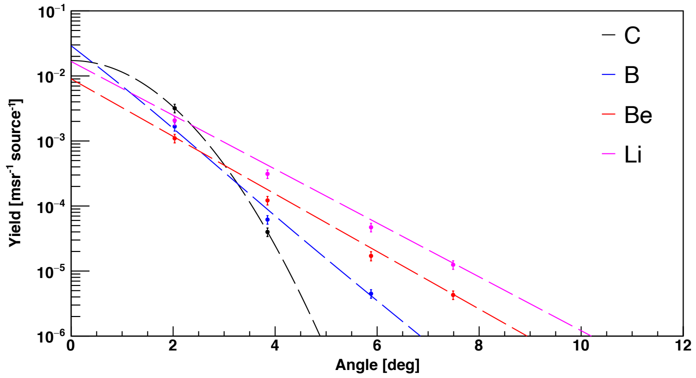
Angular distribution

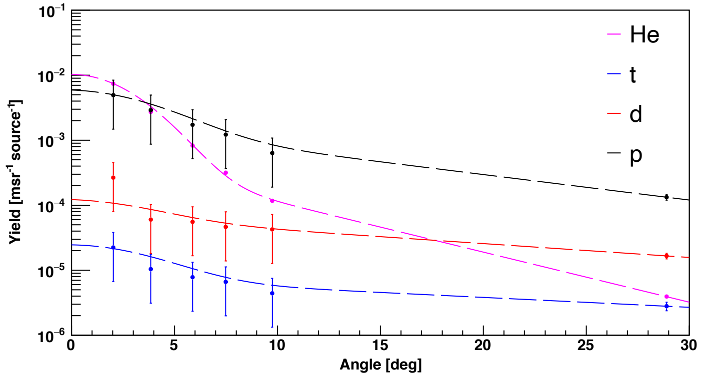




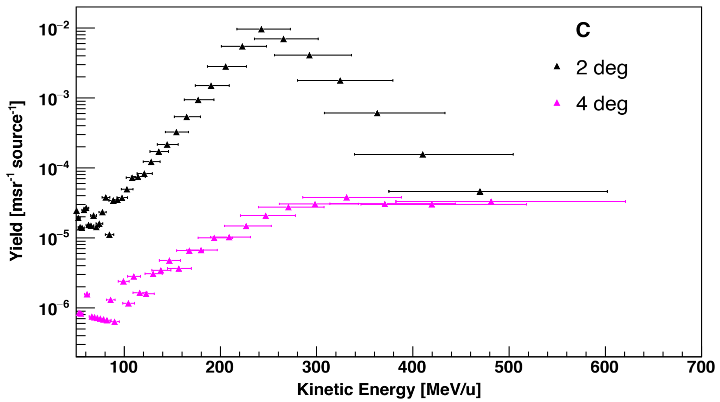
Compact bone data

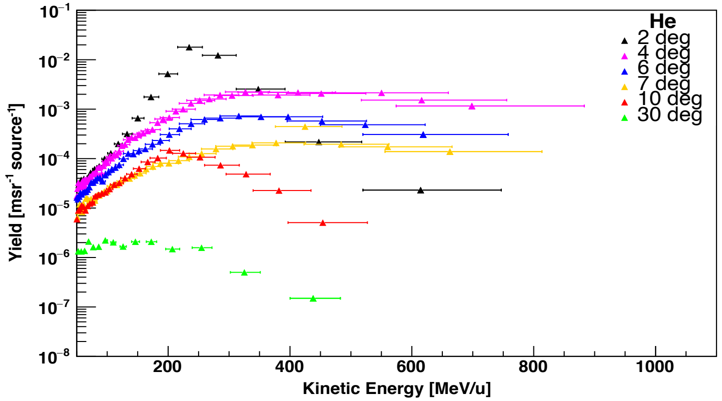
Angular distribution

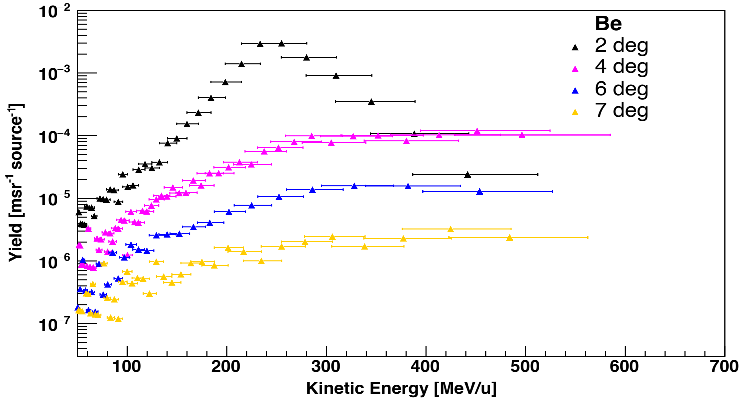


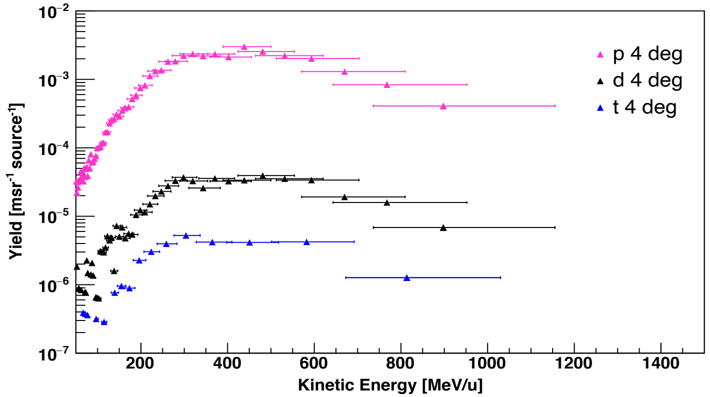


Energy distribution

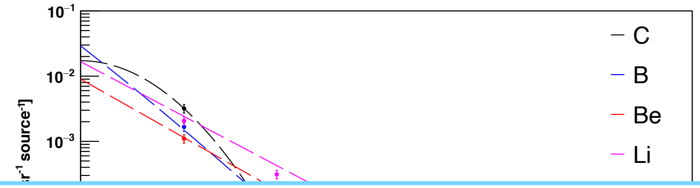


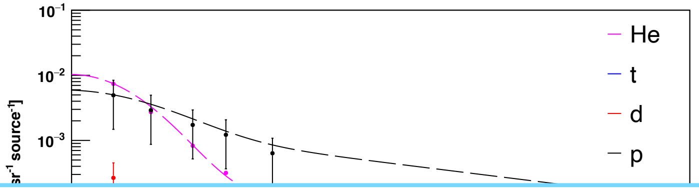




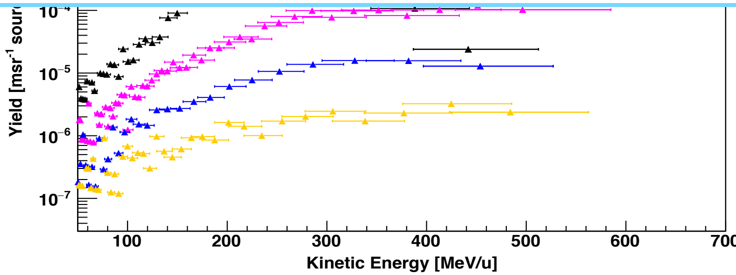


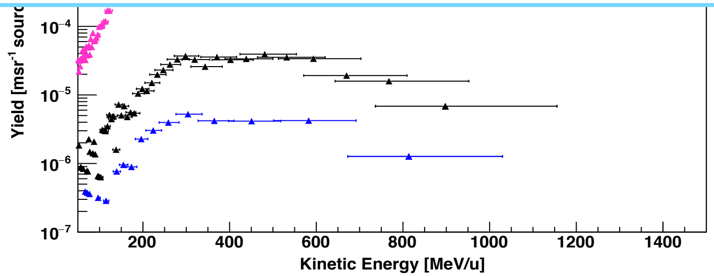
Compact bone data





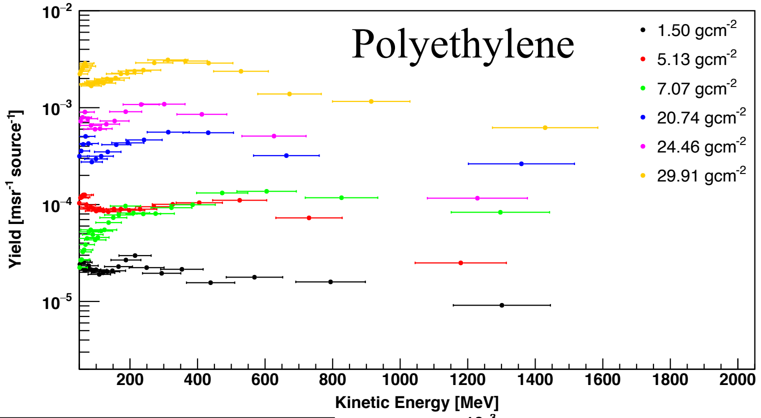
- Primary ions and heavy particles down to Li detected up to ~10 deg
- He and H fragments identified at angles > 10 deg
- P and He fragments are the most abundant species generated, dominating the spectrum in a narrow forward cone (0 - 5 deg)
- Energy spectra - @ 2 deg -> peak at 250 MeV/u
  - @ 4 , 6 deg –> wider distributions peaked at lower energy values when increasing the detection angles
  - Lighter fragments can double the primary beam energy

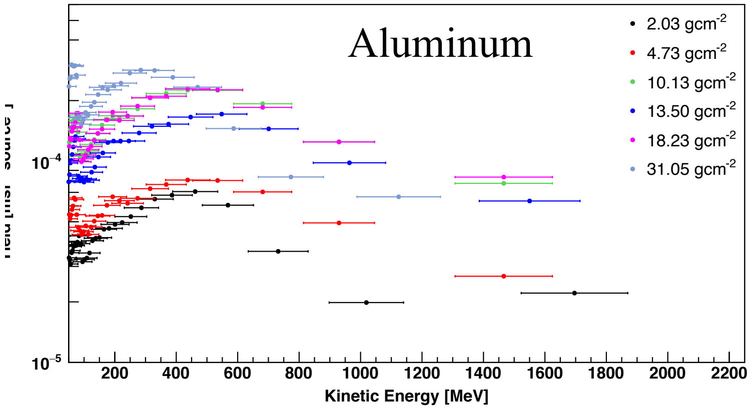




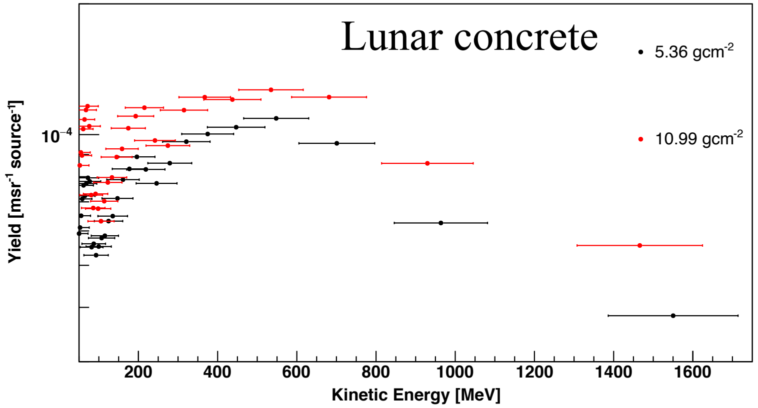
ROSSINI data – kinetic energy spectra & build-up curves

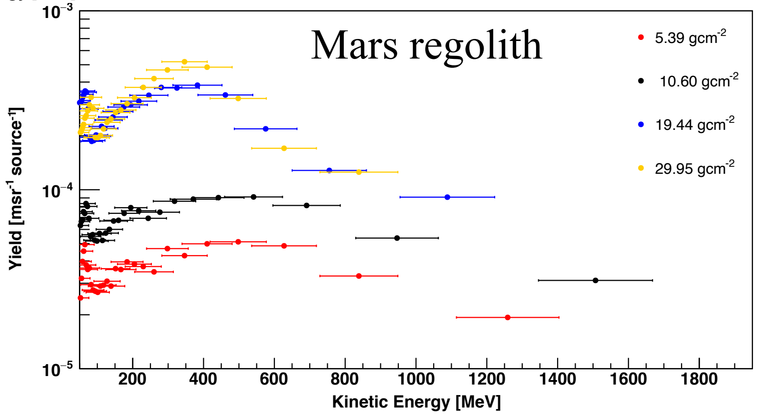
Space journey

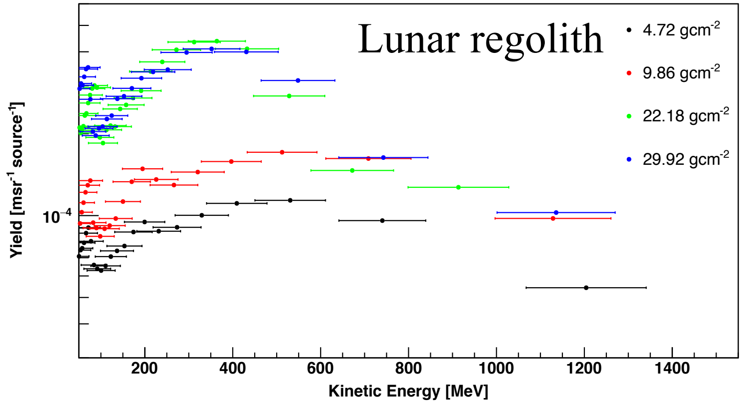




Surface habitation







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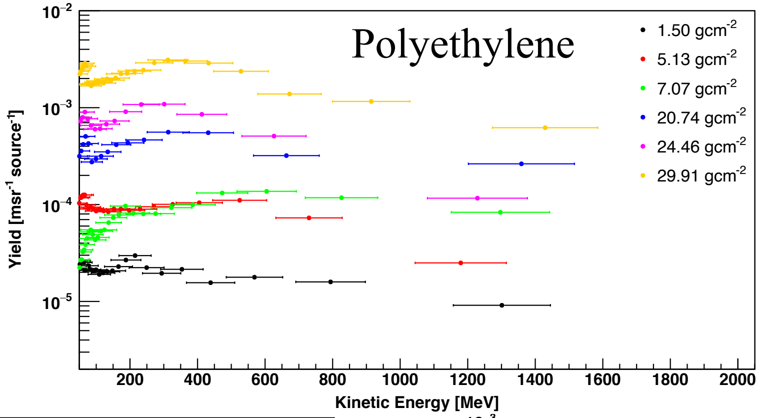
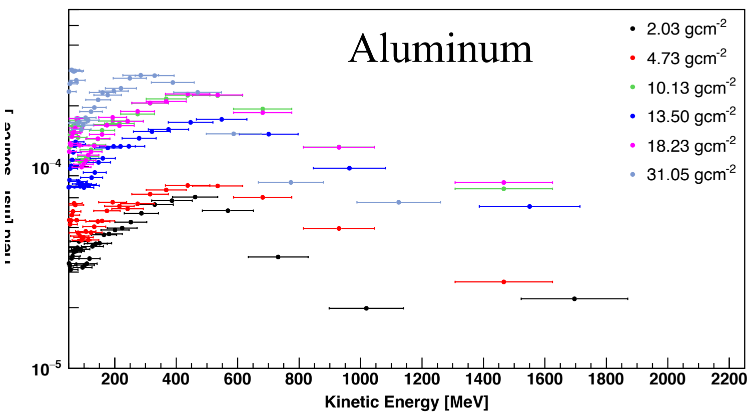
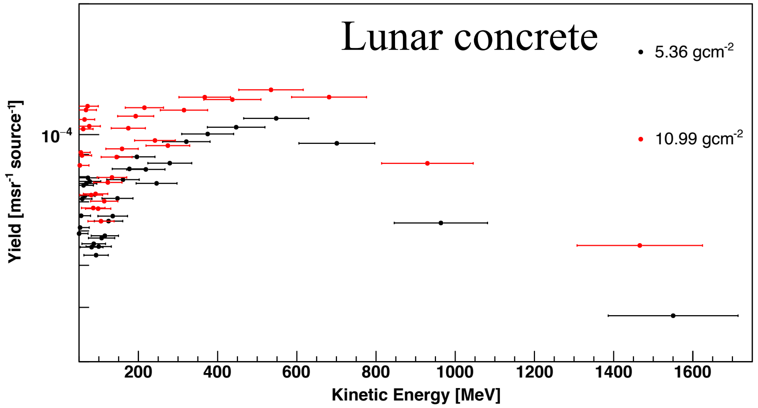
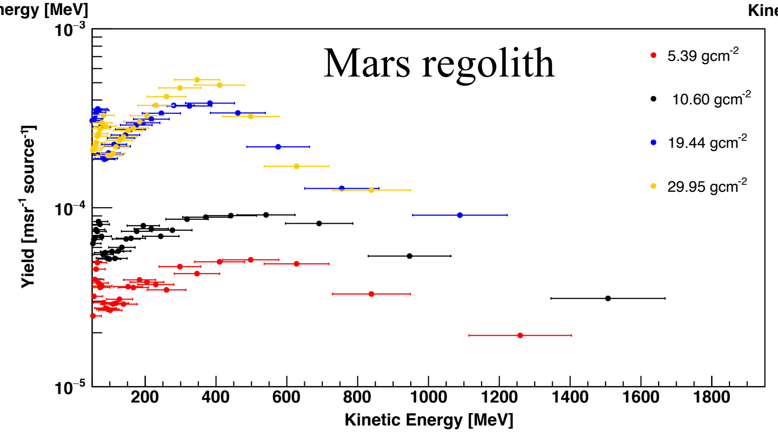
Space journey

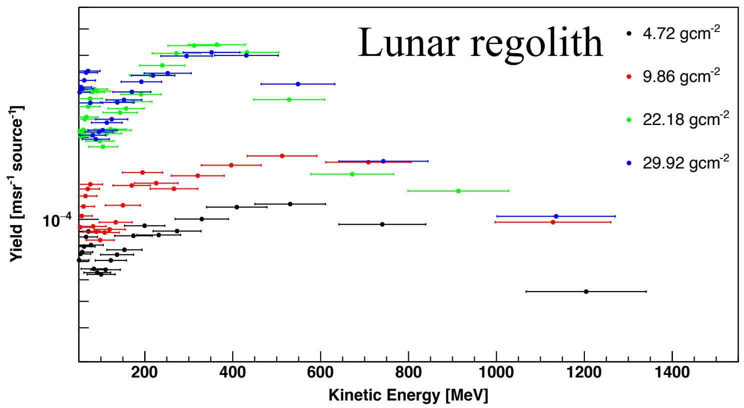




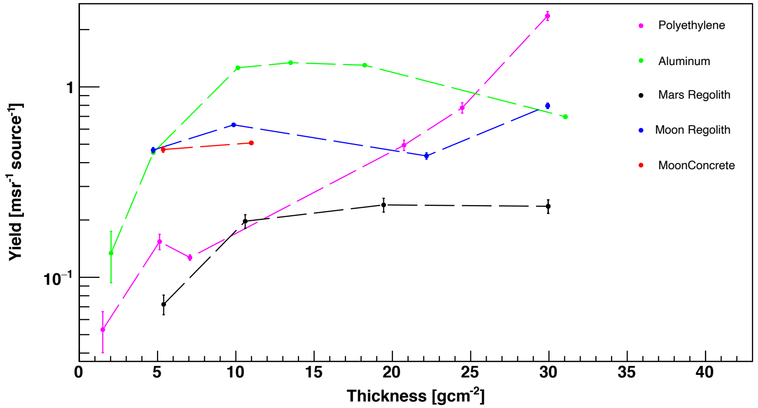
Surface habitation







Build-up curves



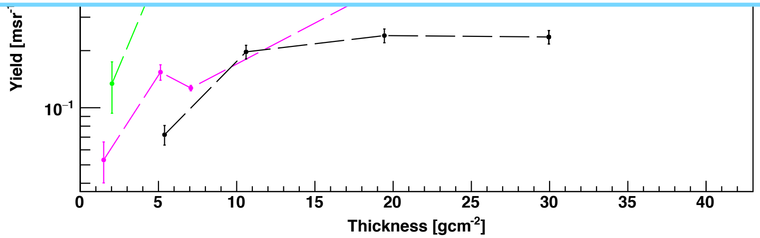
ROSSINI data – kinetic energy spectra & build-up curves

In terms of secondary neutrons production :

- Energy spectra peaked between ~300 and 500 MeV
- The peak shifts towards lower energies at increasing target thickness
- Number of secondary neutrons produced increases with the target thickness regardless of the irradiated material
- Space journey: polyethylene best choice
- Surface habitation: Moon regolith provides a lower neutrons production with respect to Moon concrete
- The point corresponding to the thickest aluminum target requires an additional investigation

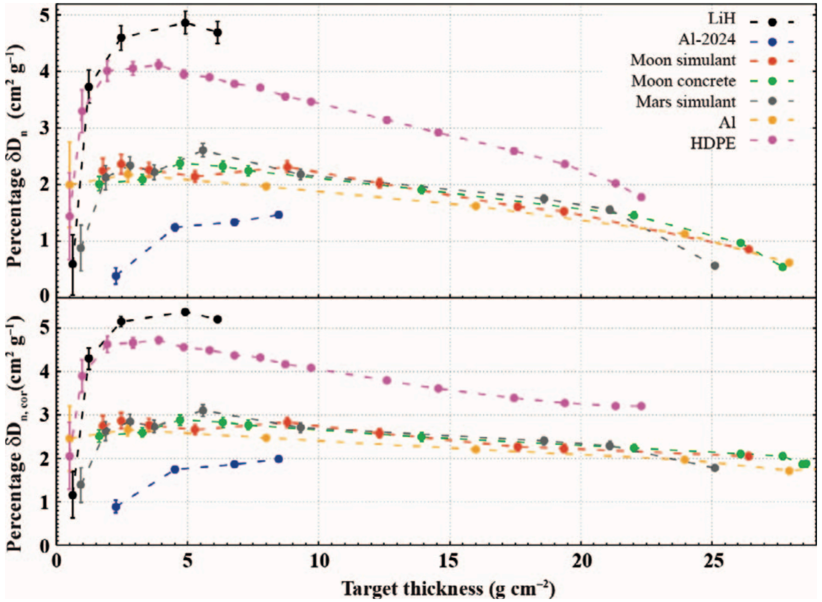
Surface habitation

Build-up curves



Conclusions adding data from *M. Giraudo et al.*

Beam: 968 MeV/u and 972 MeV/u ^{56}Fe
Target: same
Goal: dose reduction



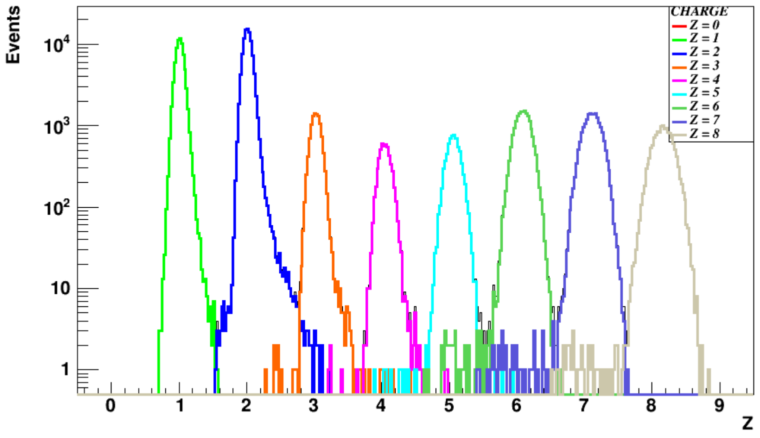
- Aluminum: almost constant independently of the target thickness
- Polyethylene: - rapid build-up in the first 2 g/cm^2 followed by a slow drop at larger thickness
  - polyethylene reduces the dose between ~15% and ~50% more than aluminum
- Moon regolith and Mars regolith and Moon concrete: dose reduction almost the same

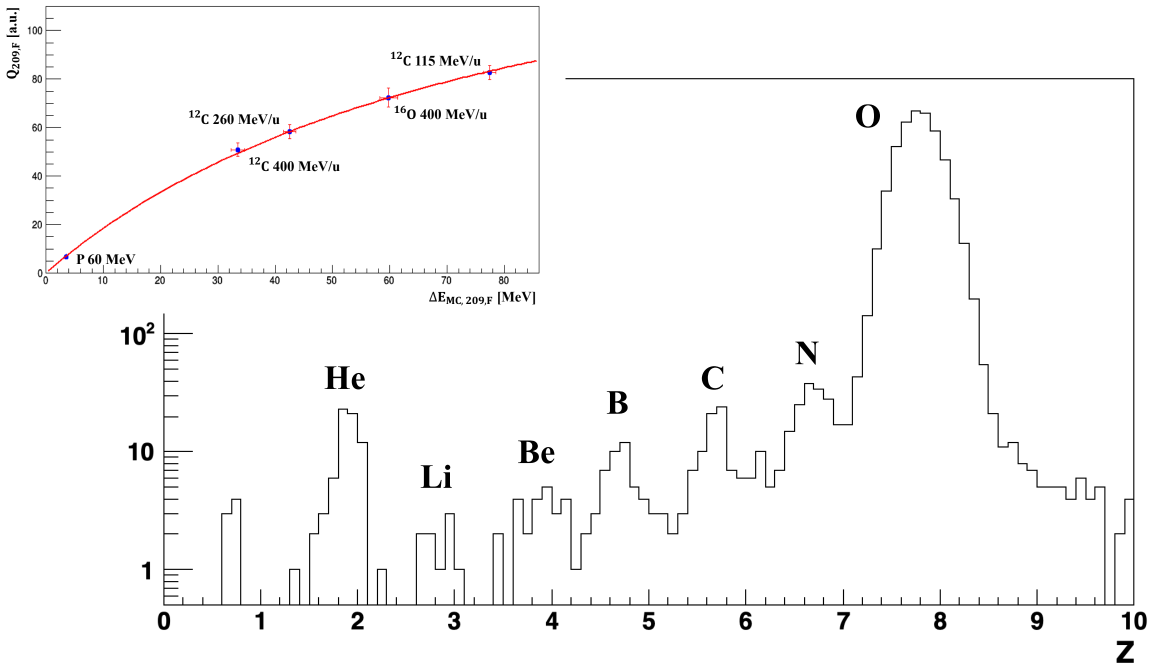
- Polyethylene: best compromise between low neutrons production and dose reduction capability -> ideal material for the spacecraft hull shielding
- Moon concrete: always lower dose reduction with respect to Moon regolith
- Additional target materials and thicknesses should be irradiated with ^{58}Ni and other light and heavy ions to provide a more complete comparison of candidate shielding materials

FOOT – fragments identification

$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi N_A m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Fluka simulation ^{16}O (200 MeV/u) → C_2H_4



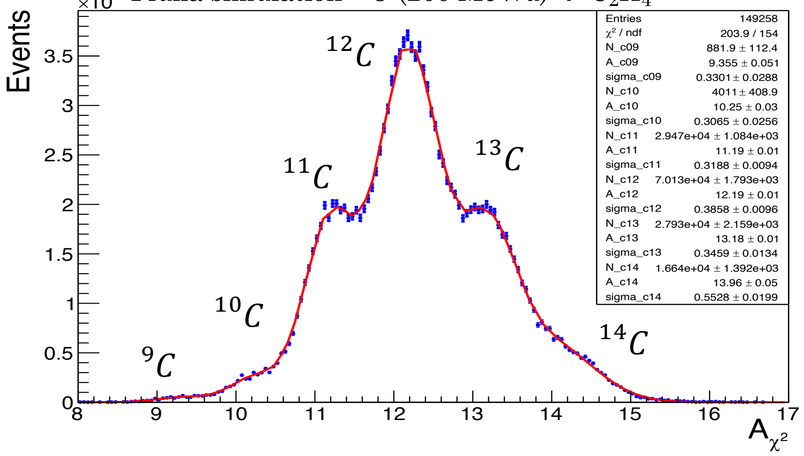


$$A_1 = \frac{\boldsymbol{p}}{U\boldsymbol{\beta\gamma}c}$$

$$A_2 = \frac{\boldsymbol{E_k}}{Uc^2(1-\boldsymbol{\gamma})}$$

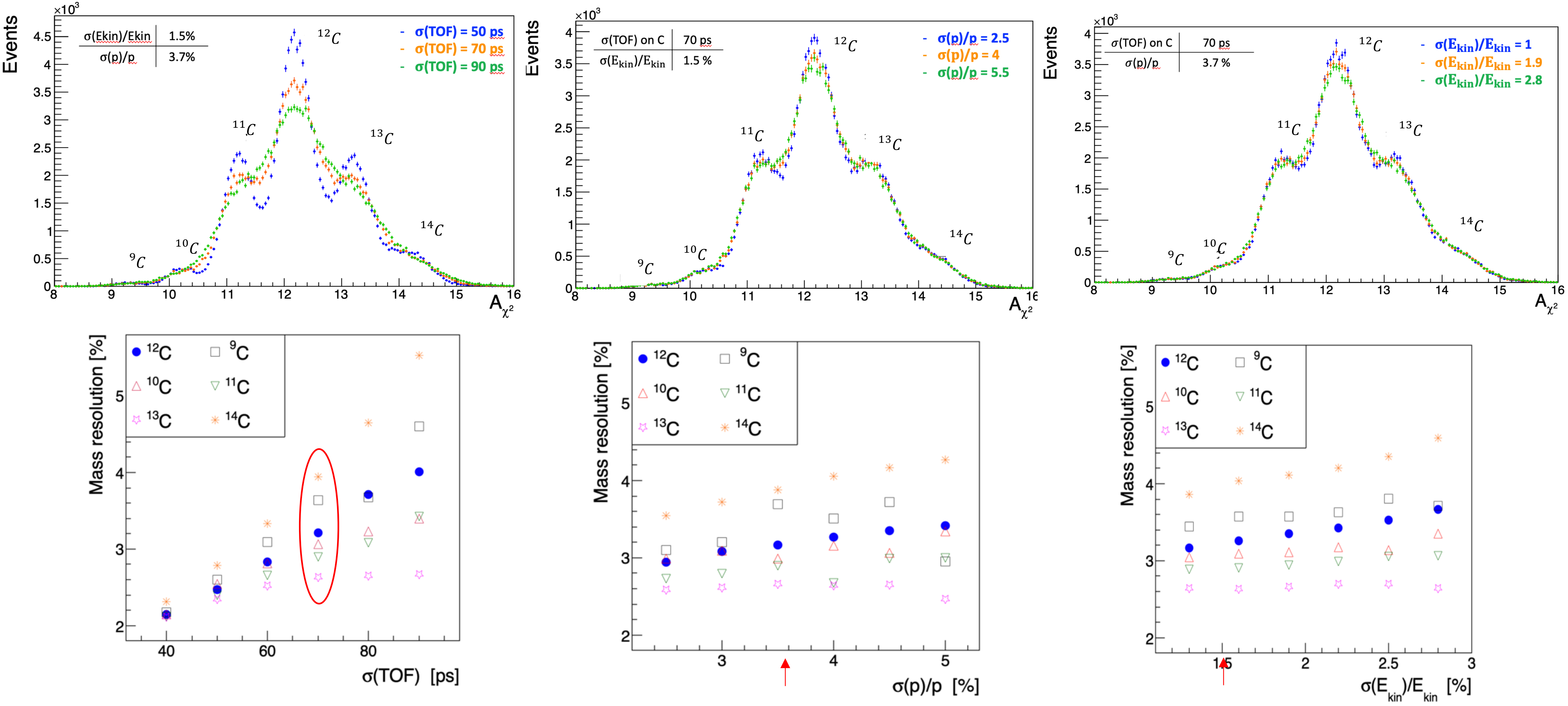
$$A_3 = \frac{\boldsymbol{p}c^2 - \boldsymbol{E_k}^2}{2Uc^2\boldsymbol{E_k}}$$

Fluka simulation ^{16}O (200 MeV/u) → C_2H_4



- Charge res: 2% (^{16}O) – 6% (^{1}H)
- Mass res: 3.5% (^{16}O) – 4.5% (^{1}H)

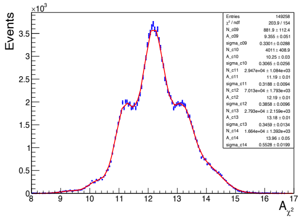
FOOT – performances study

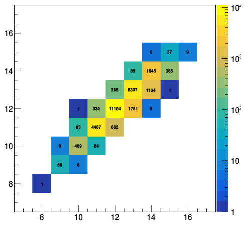


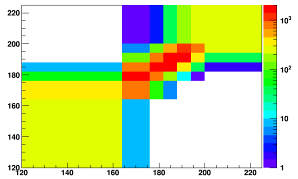
σ(TOF) is the most sensible parameter in terms of isotope identification

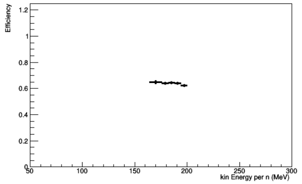
FOOT - cross sections reconstruction

Y_f → $Y_f\text{-}Bkg_f$ → $(Y_f - Bkg_f)^U$ → $\frac{(Y_f - Bkg_f)^U}{\varepsilon_f}$

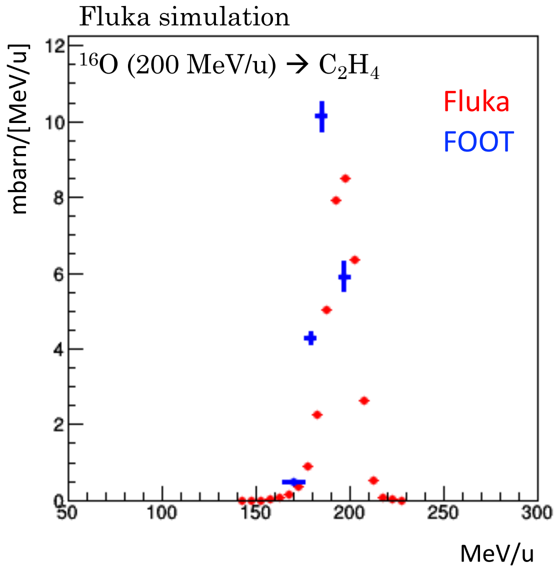




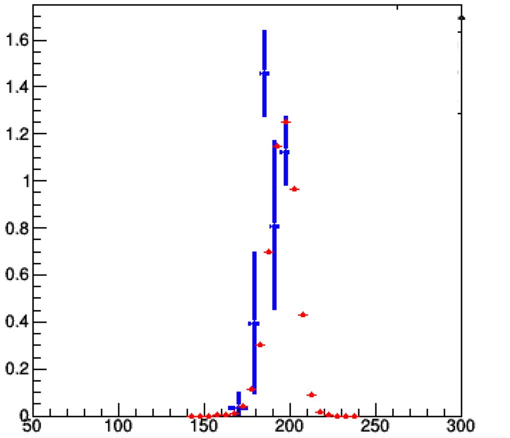




$$\frac{d\sigma_f}{dE_{kin}} = \frac{(Y_f - Bkg_f)^U}{N_{Prim}\,.\,N_t\,.\,\Omega_{Ekin}\,\epsilon_f}$$



$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$



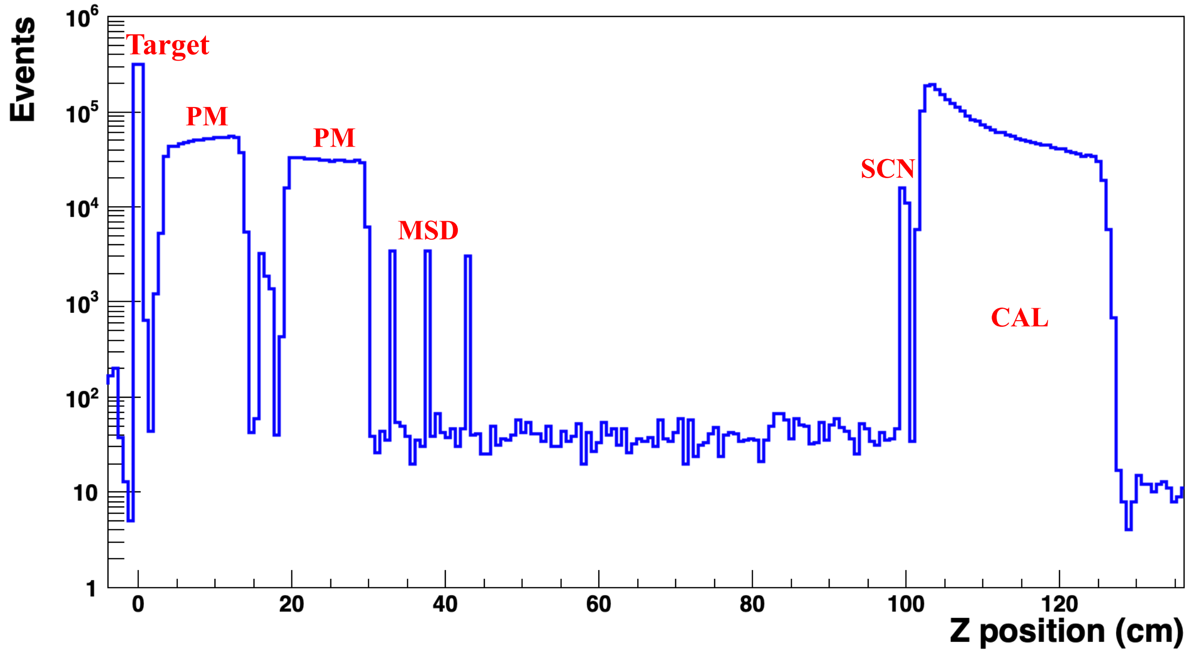
Total Cross Section

$$\sigma_f = \frac{(Y_f - Bkg_f)^U}{N_{Prim}\,.\,N_t\,.\,\epsilon_f}$$

Direct kinematics :

- $\frac{\sigma_{FLUKA}}{\sigma_{FOOT}} < 25\%$ for all C isotopes
- H by difference : $\frac{\sigma_{FLUKA}}{\sigma_{FOOT}} \approx 8\ \%$

FOOT - future



Future … let’s play with FOOT and neutrons!