FOOT: FragmentatiOn Of Target experiment

Christian Finck, Marie Vanstalle and Desis team
on behalf of the FOOT collaboration

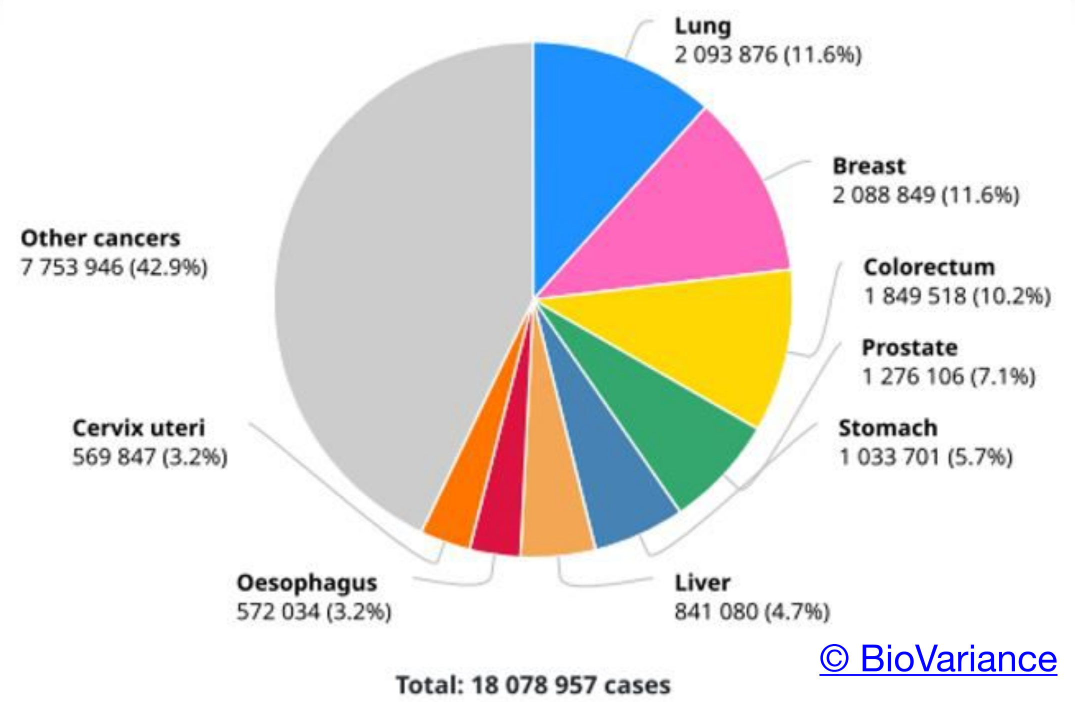
FramentatiOn
Of Target

Institut Pluridisciplinaire
Hubert CURIEN
STRASBOURG

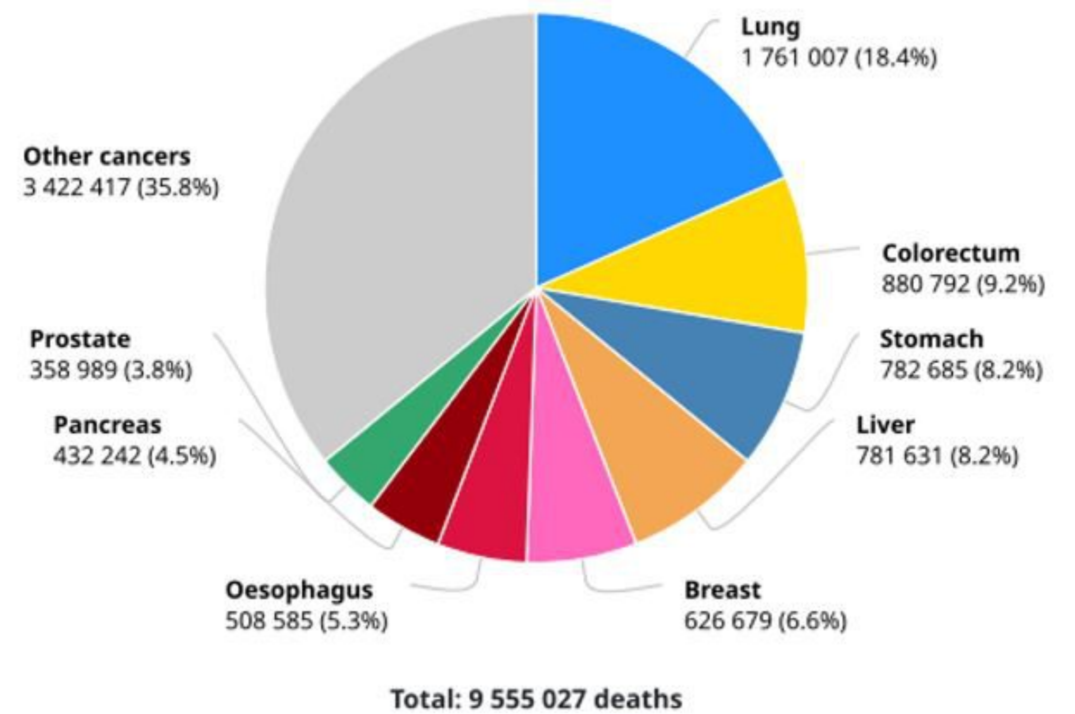
Cancer occurrence

❑ Cancer treatments are usually structured around three axis:

- Surgery
- Chemotherapy
- Radiotherapy: → X-rays → Ions (p, He, C, O)



© BioVariance



➡ Survival rate after 5 years: ~50%

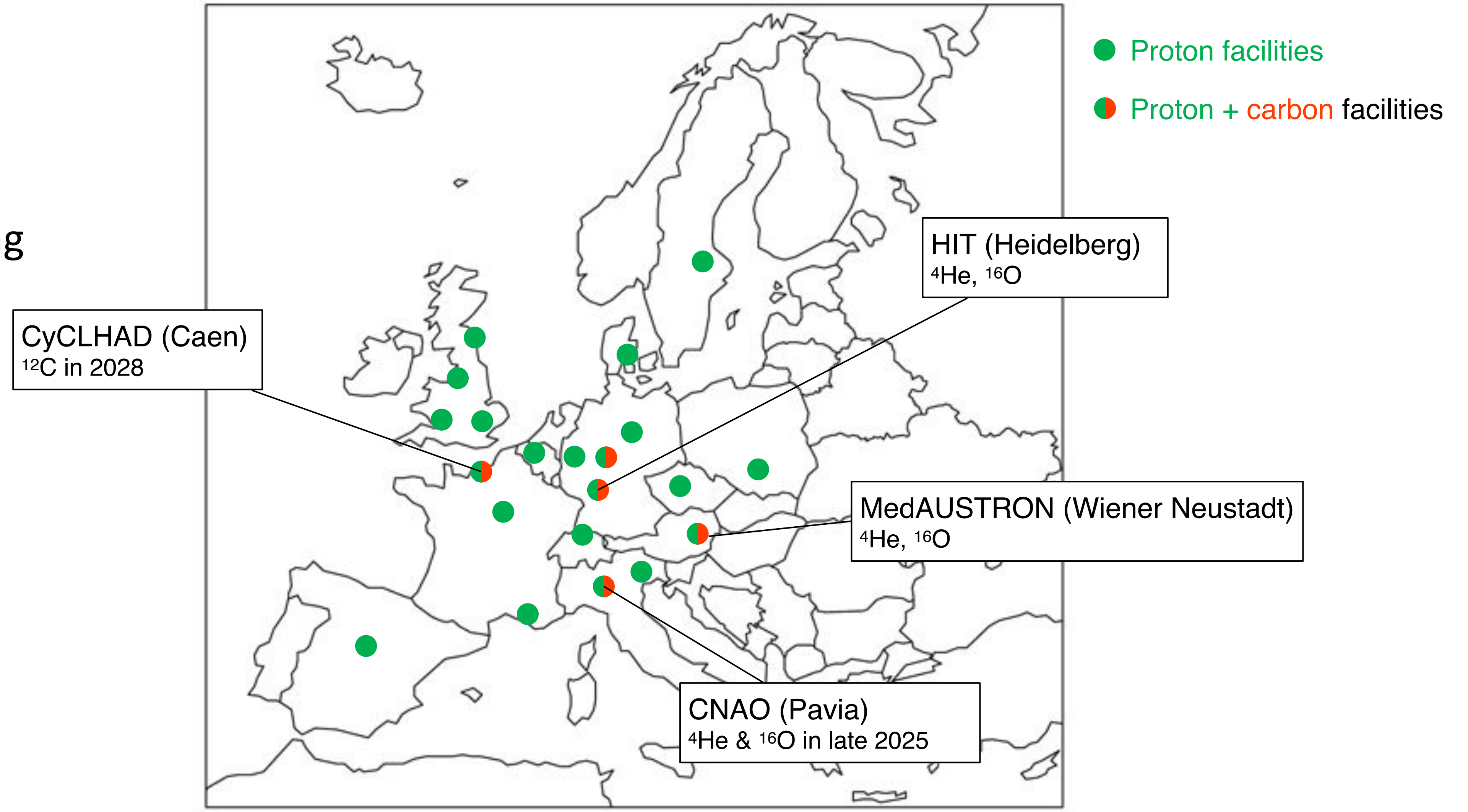
Hadrontherapy facilities in the world

- More than 300,000 patients treated with protontherapy in the world
- 50,000 with 12C therapy (Statistics from PTCOG website, up to 2022)

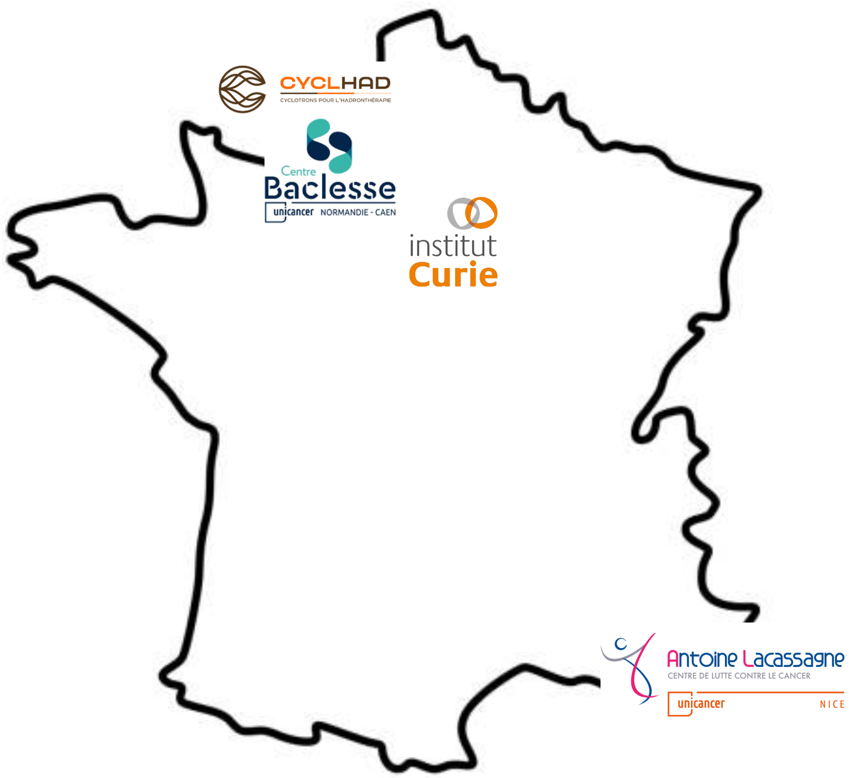
➡Main indications: pediatric cancers, head & neck cancers, deep-seated tumors,…

Hadrontherapy facilities in Europe

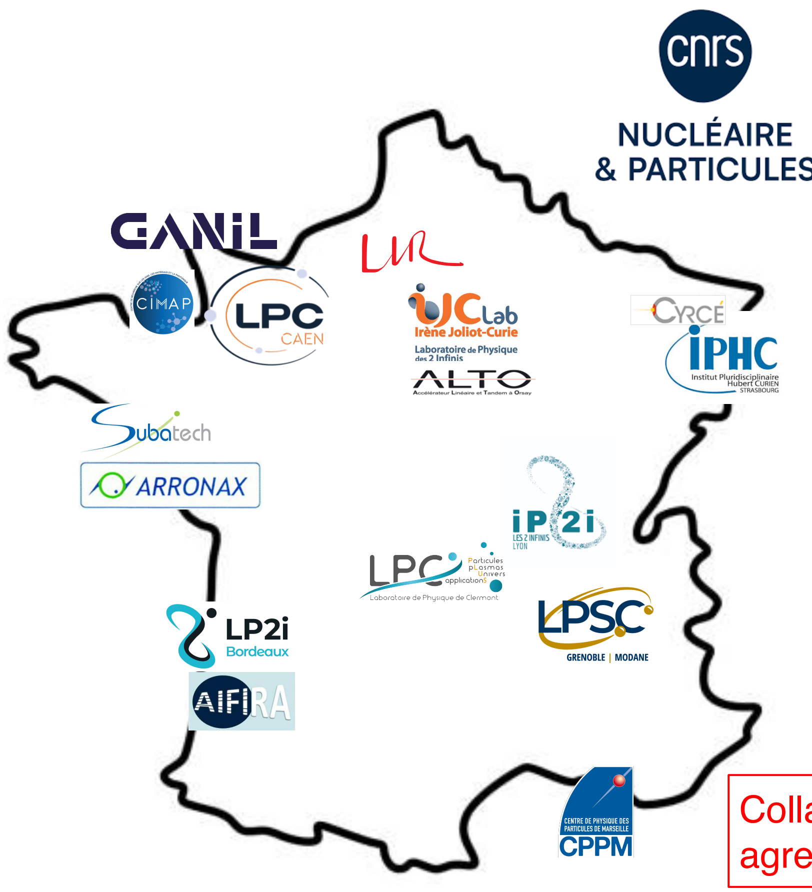
- 22 proton therapy centres:
- Carbon therapy centres:
  - 3 in used
  - One under commissioning
- ^{4}He and ^{16}O under test



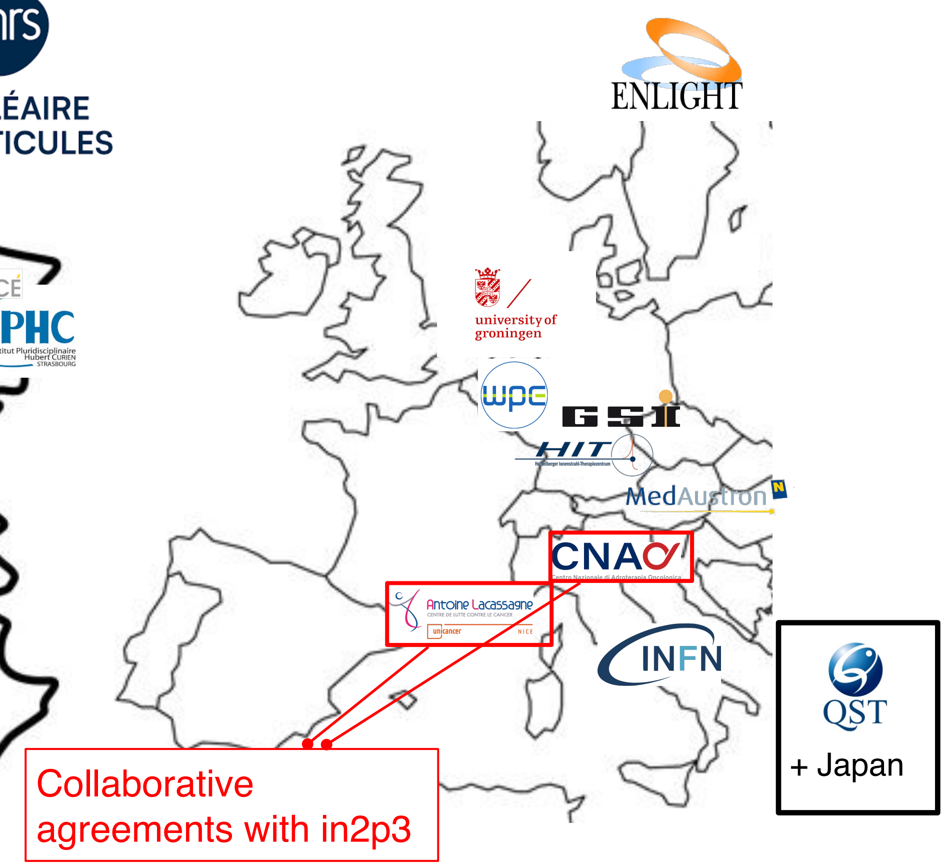
Hadrontherapy in France



Clinical facilities



IN2P3 laboratories & platforms



Collaborations (2025 status)

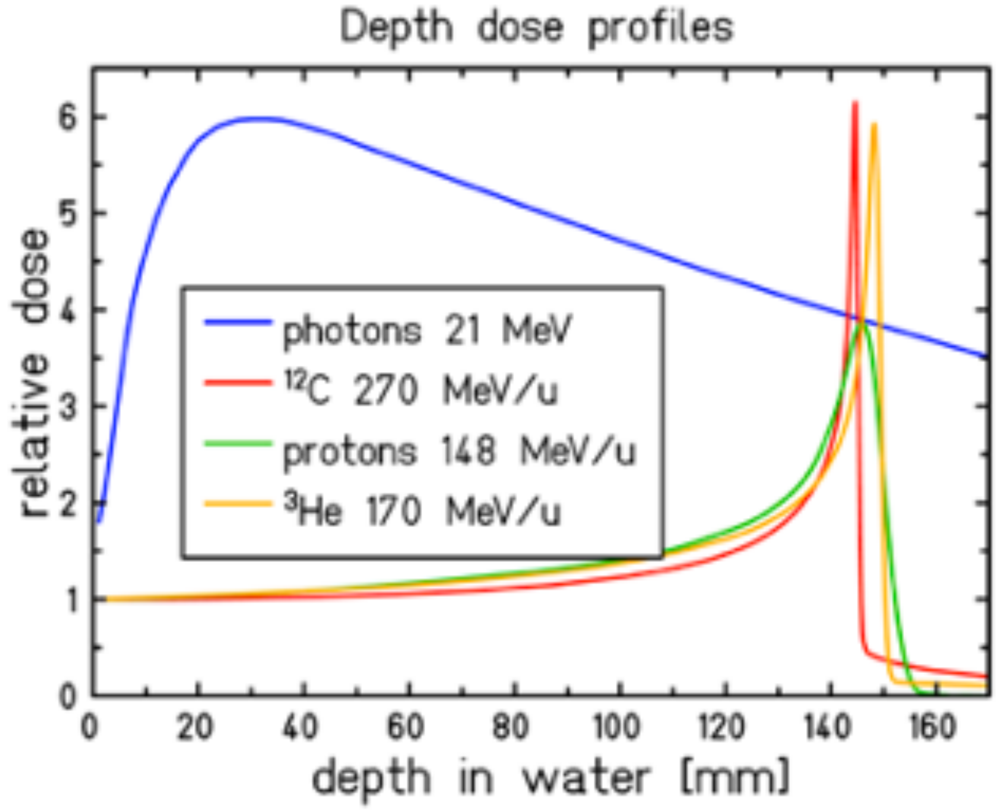
Courtesy of M. Vanstalle

➡ Only few treatment centres but many laboratories/platforms are involved with collaborations with centres

Ion effects (i)

❑ Physical aspects:

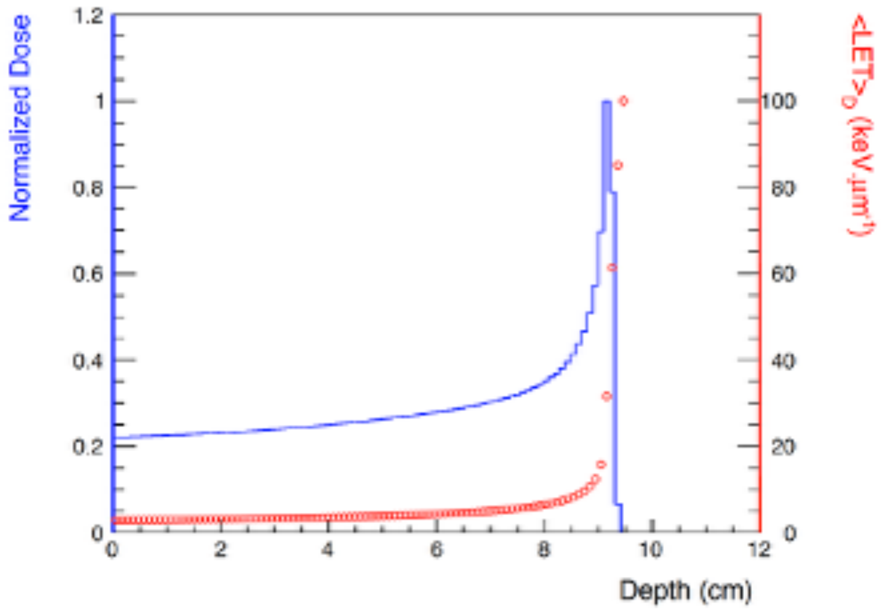
- High dose at the end of ion path (Bragg Peak) ≠ X-rays
- Due to stopping power of ions: $\frac{dE}{dx} \propto \frac{(mZ^2)}{E}$



From **Kraemer et al.**, *"Helium ions for radiotherapy? Physical and biological verifications of a novel treatment modality"* , Med. Phys. (2016).

- Linear Energy Transfer (LET):

$$LET = \frac{dE - E_\delta}{dx}$$

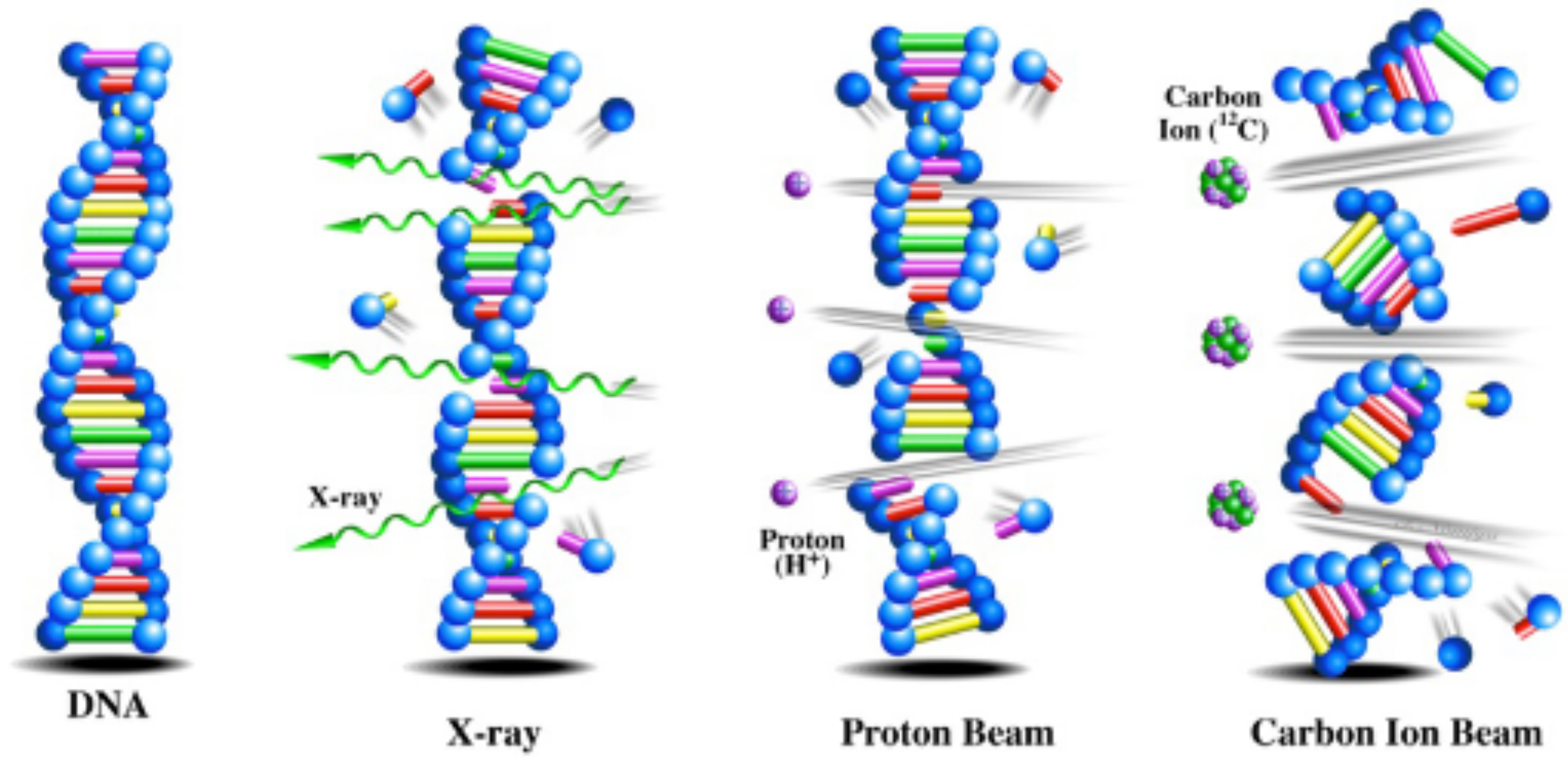


➡ Biological dose directly linked to LET through

Ion effects (ii)

❑ Biological - chemical aspects:

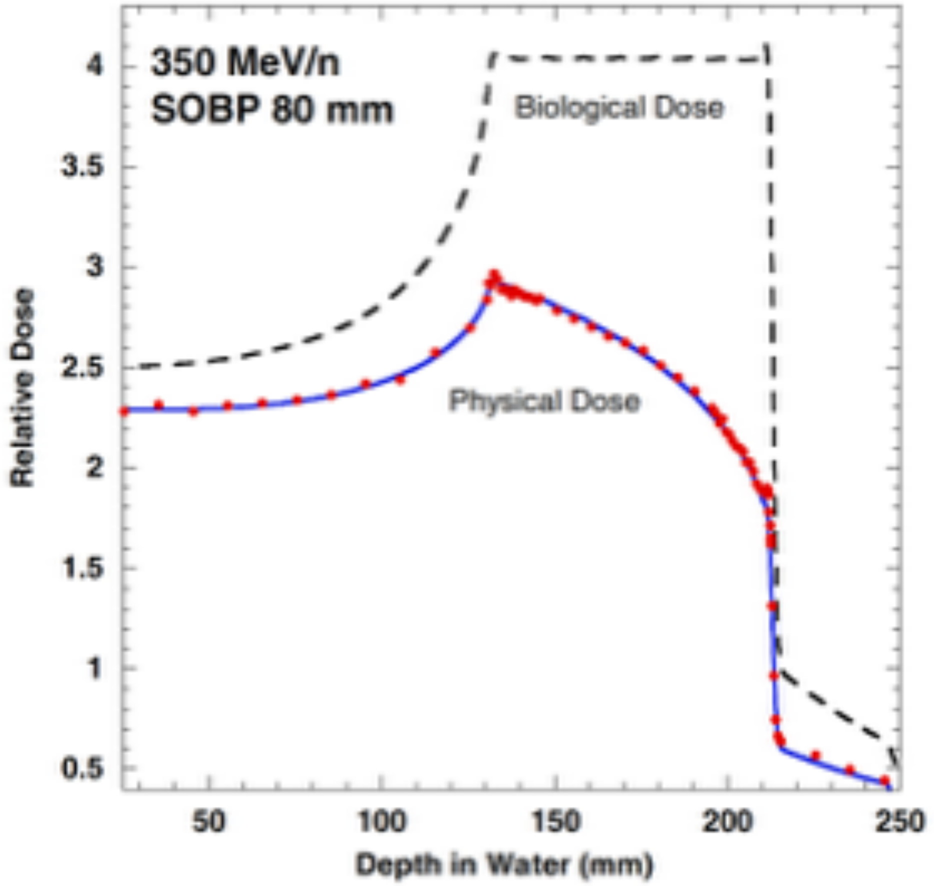
- Direct effect: single-strand (SSB) or double-strand breaks (DSB) of the cell DNA
- Indirect effect: water radiolysis ⟹ free radicals ⟹ cell damages

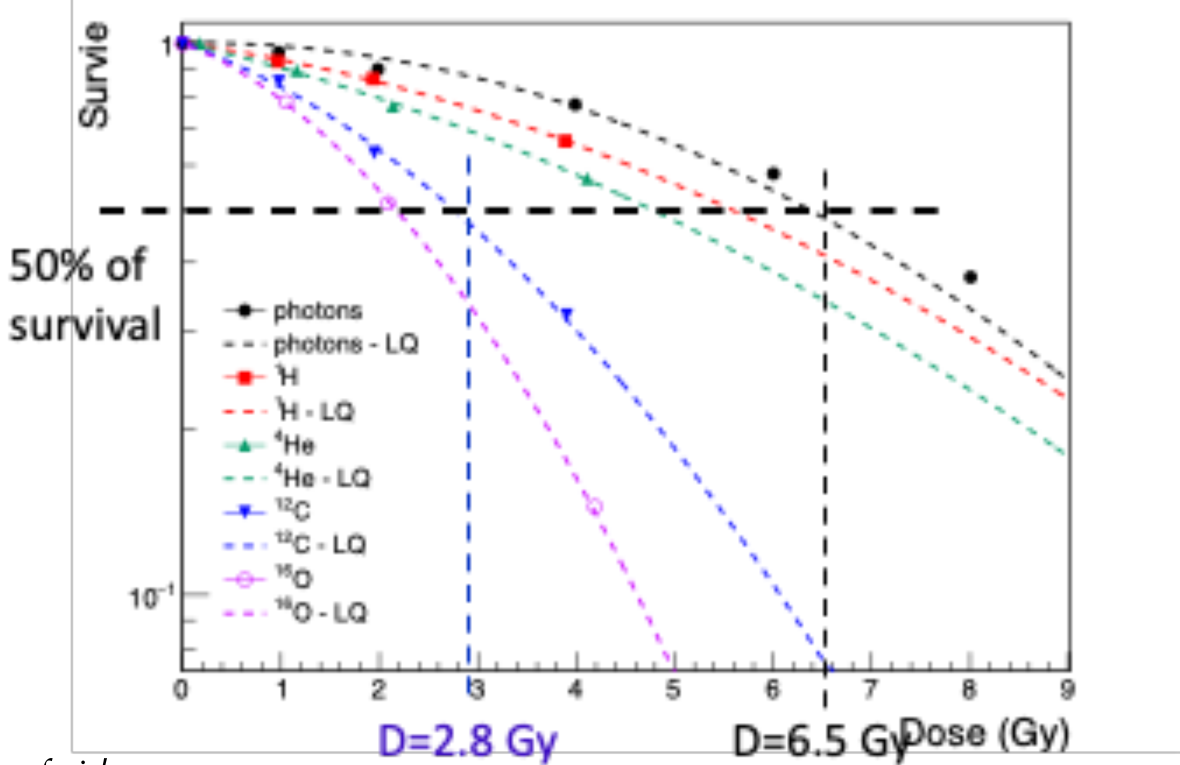


➡ Proportion of direct and indirect effects ∝ LET

Ion effects (iii)

- Biological effects of ions quantified by RBE:
  - RBE defined as: $RBE = \frac{D_X}{D_{ion}}$ where D is the dose (energy deposited per mass)
  - Measured with survival curves



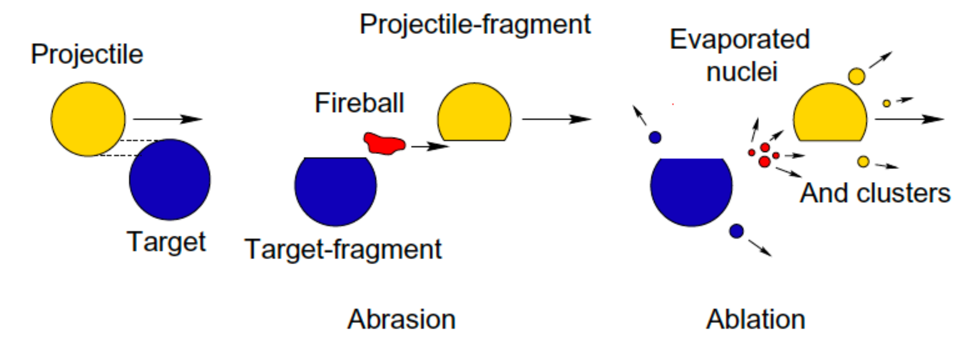


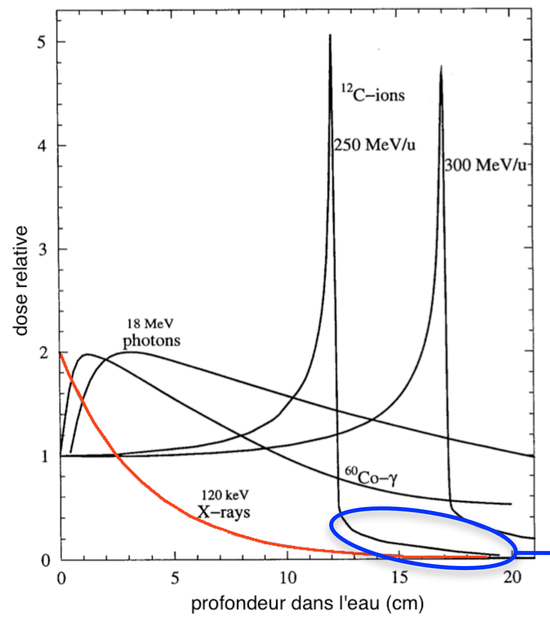
From **Sakama et al.**, *"Design of ridge filters for spread-out Bragg peaks with Monte Carlo simulation in carbon ion therapy"*, Phys. Med. Biol.(2012).

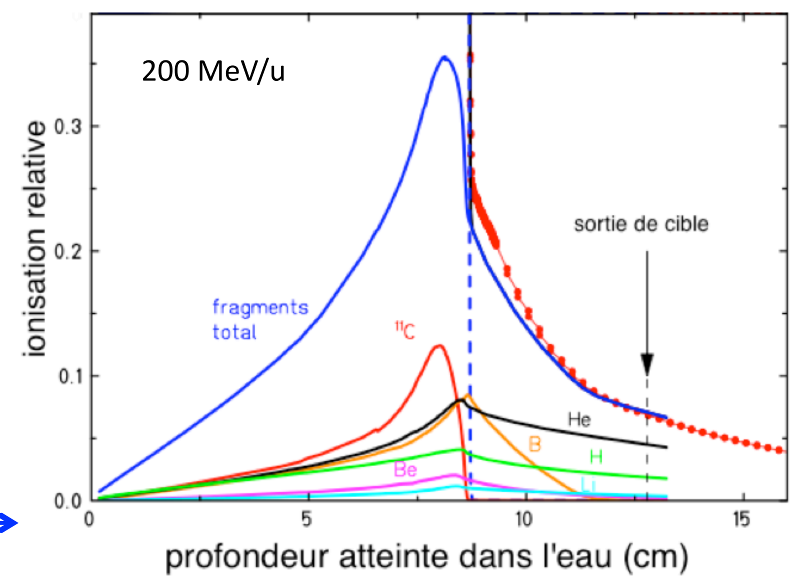
➡ Physical dose needs to be corrected by RBE to obtain the "biological dose"

Ion effects (iv)

- Nuclear reactions (i):
  - Beside ionisation the nuclei undergo nuclear processes

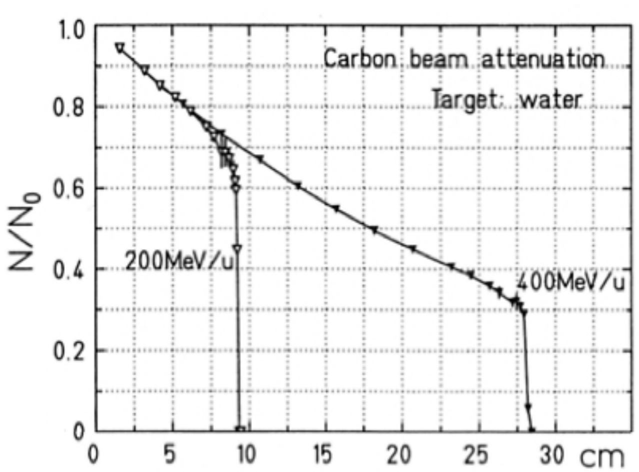




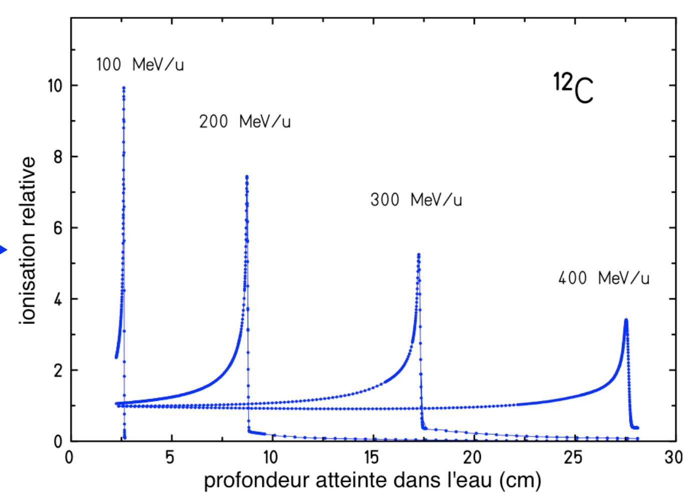


From **Gunzert-Marx et al.**, *"Secondary beam fragments produced by 200 MeV/u ^{12}C ions in water and their dose contributions in carbon ion radiotherapy"*, New J. Phys. (2008).

E. Haettner (2006)



$$N(x) = N_0 e^{-x/\lambda}$$



D. Schardt (2010)

➡ Beam consumption

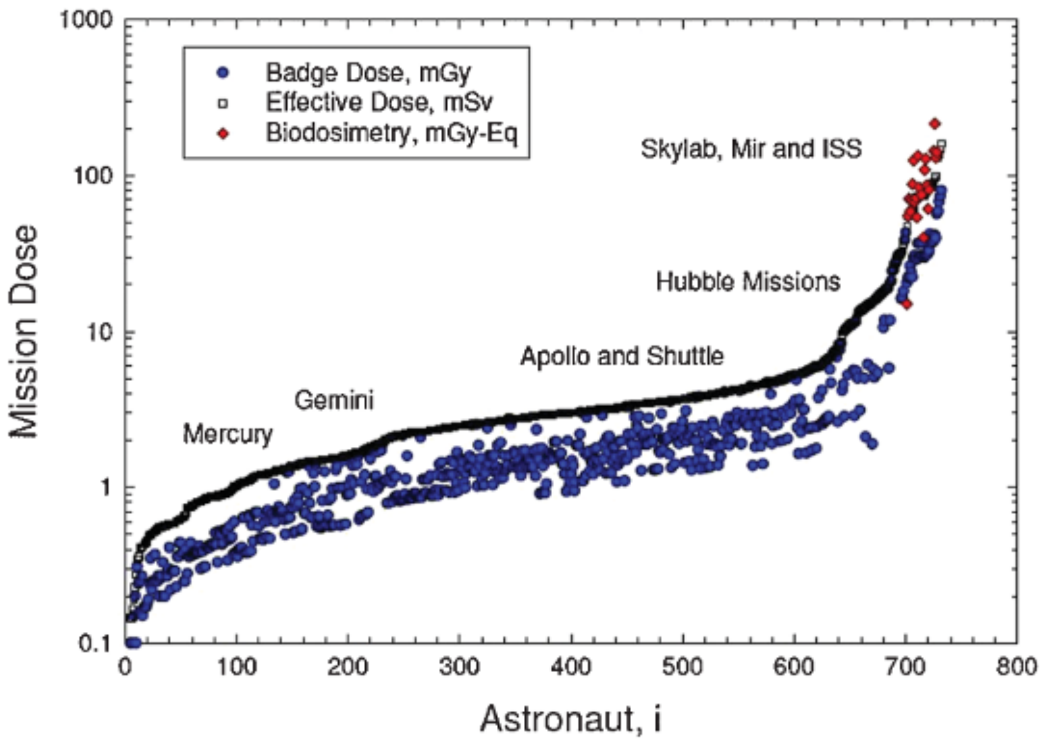
➡ Extra dose

Ion effects (v)

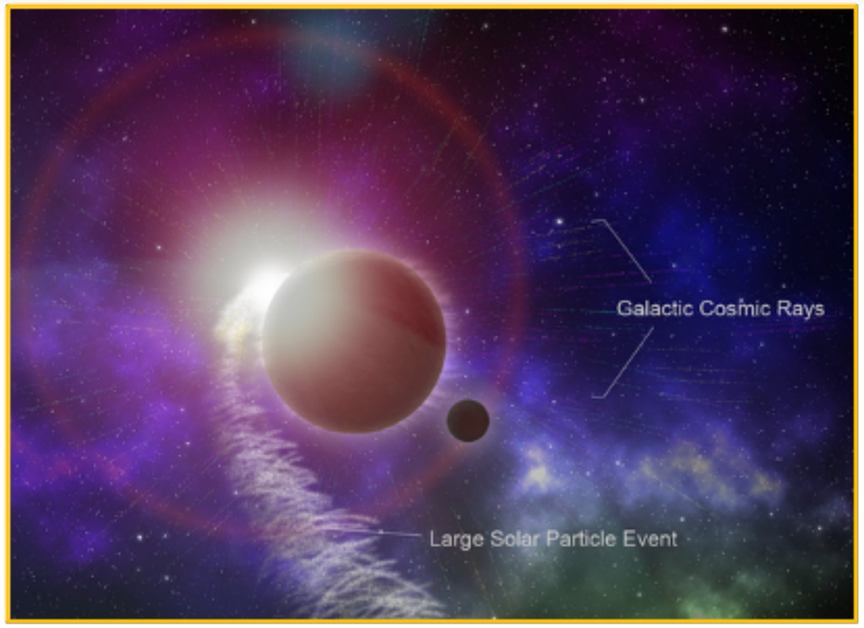
❑ Nuclear reactions (ii):

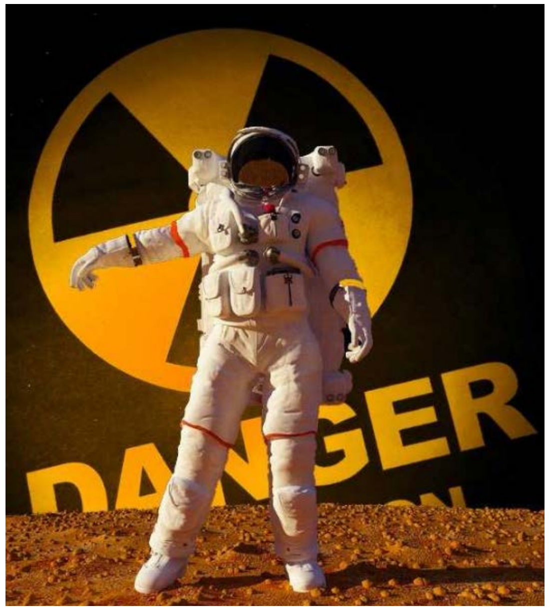
- GCR (Galactic Cosmic Rays) and 2dary particles produced by GCR

➡ main hindrance for long-term exploratory missions in deep space



From **Cucinotta et al.**, "Physical and Biological organ dosimetry analysis for International Space Station Astronauts", Radiat. Res. (2008).



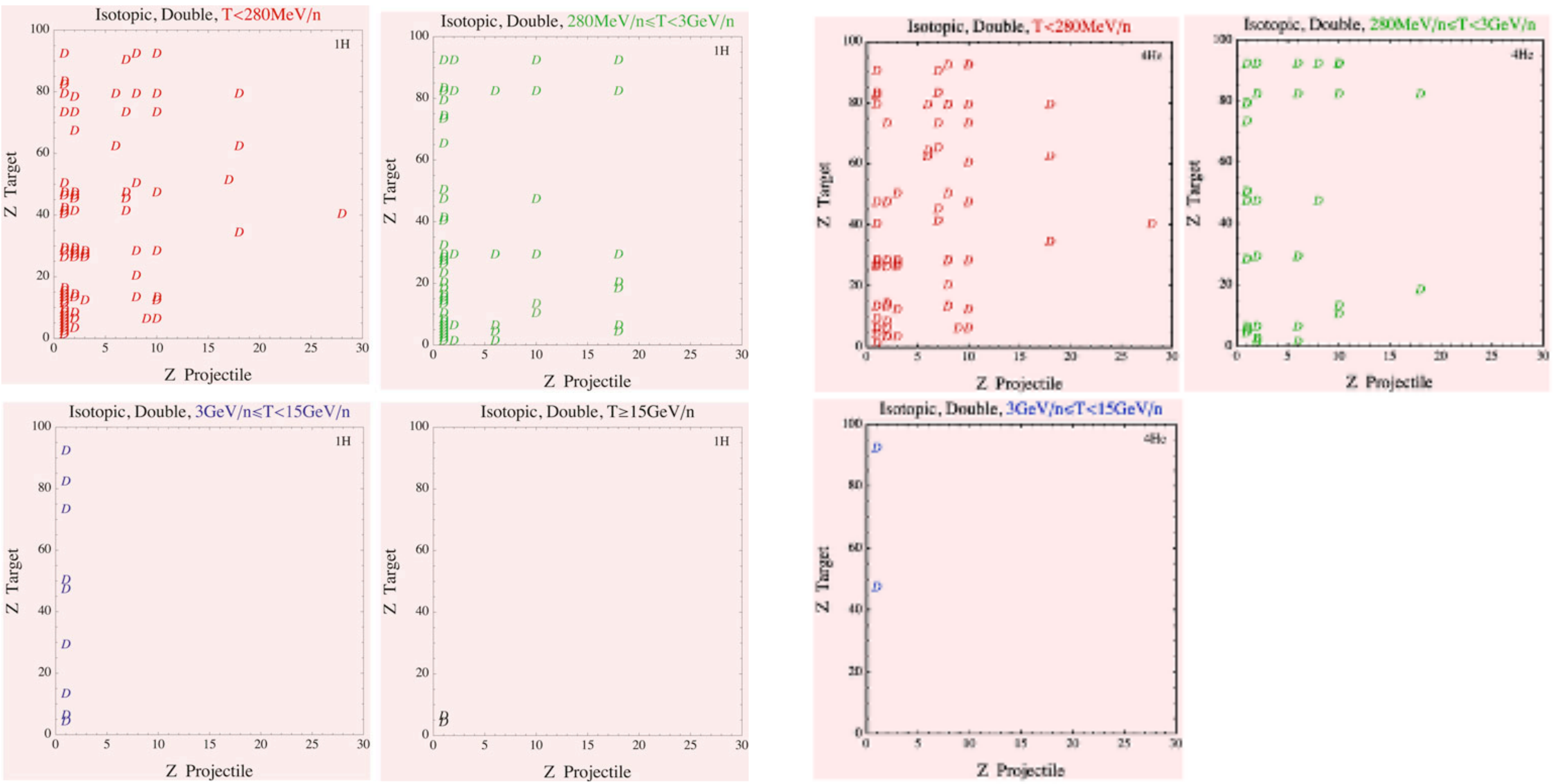


➡ Extra dose during space journey

- p, He, Li, C, O, Fe isotopes (the most common in space) impinging on spacecraft shielding

Cross-section measurements (i)

- Why ?
  - Lack of data at energies between 100 MeV/n and 10 GeV/n (energies of interest for space applications)



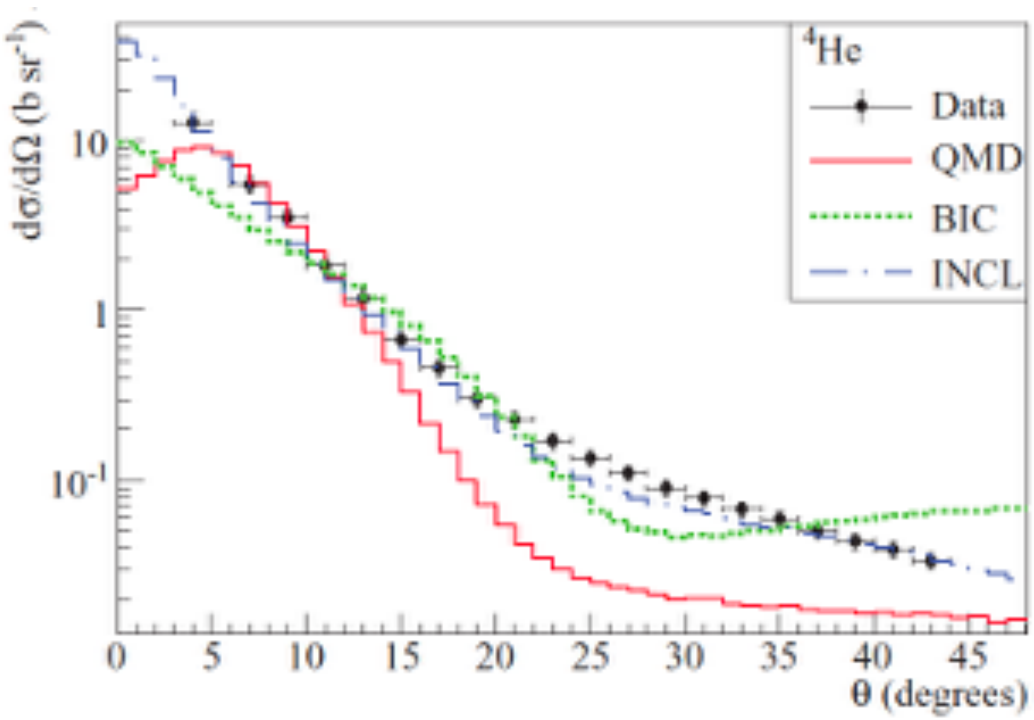
From **Norbury et al.**, *"Nuclear data for space radiation"*, Radiat. Meas. (2012)

➡ For some combination beam/target no data are available

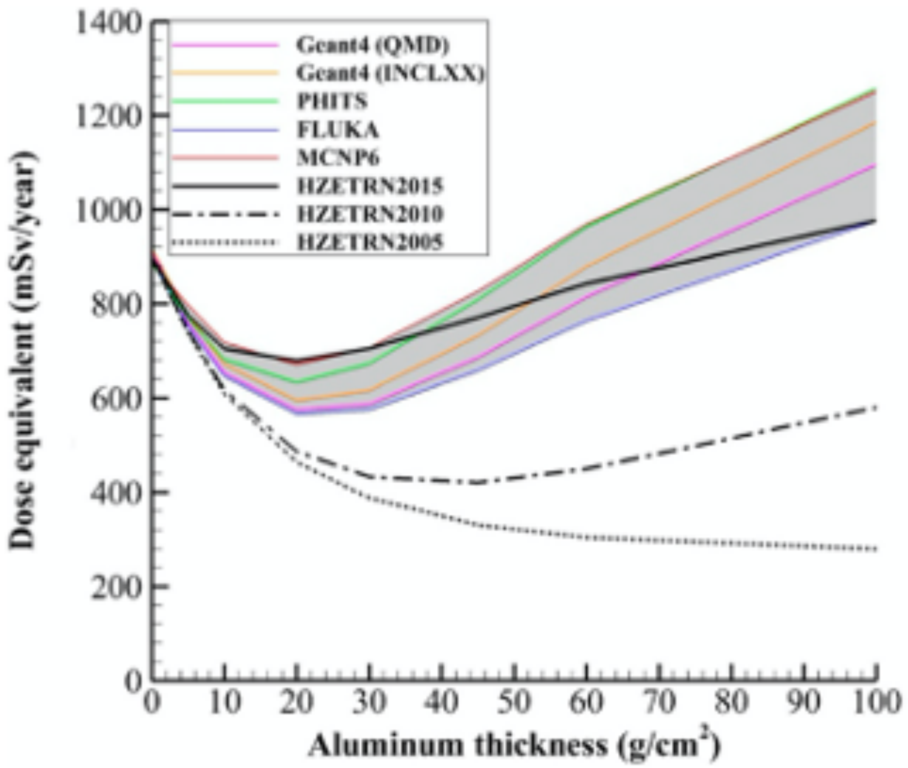
Cross-section measurements (ii)

- Why ?
  - Discrepancies between data and models:

$^{12}C(^{12}C,^{4}He)$ reaction @ 95 MeV/n



From **Dudouet et al.**, "*Benchmarking Geant4 nuclear models for hadron therapy with 95 MeV/n carbon ions*", Phys. Rev. C (2014).



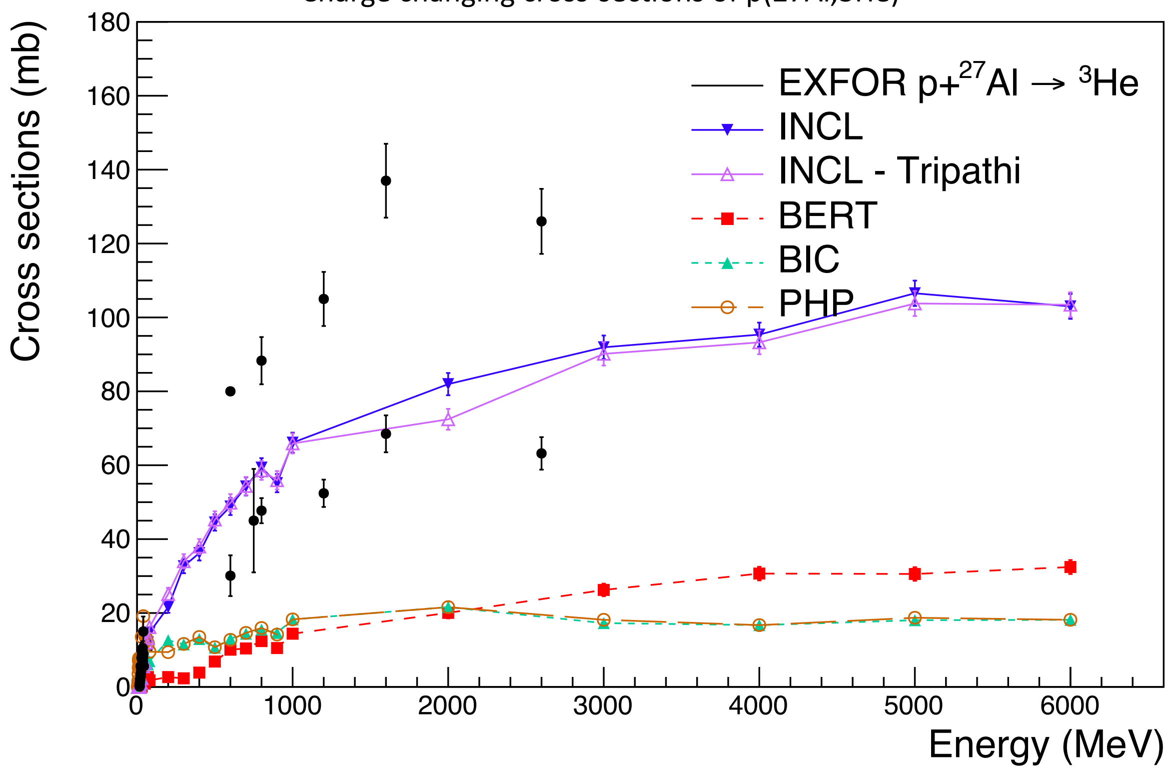
From **Norbury et al.**, "*Advances in space radiation physics and transport at NASA*", Life Sciences in Space Research (2019).

➡ No model reproduced dose or cross-section for any energy or material

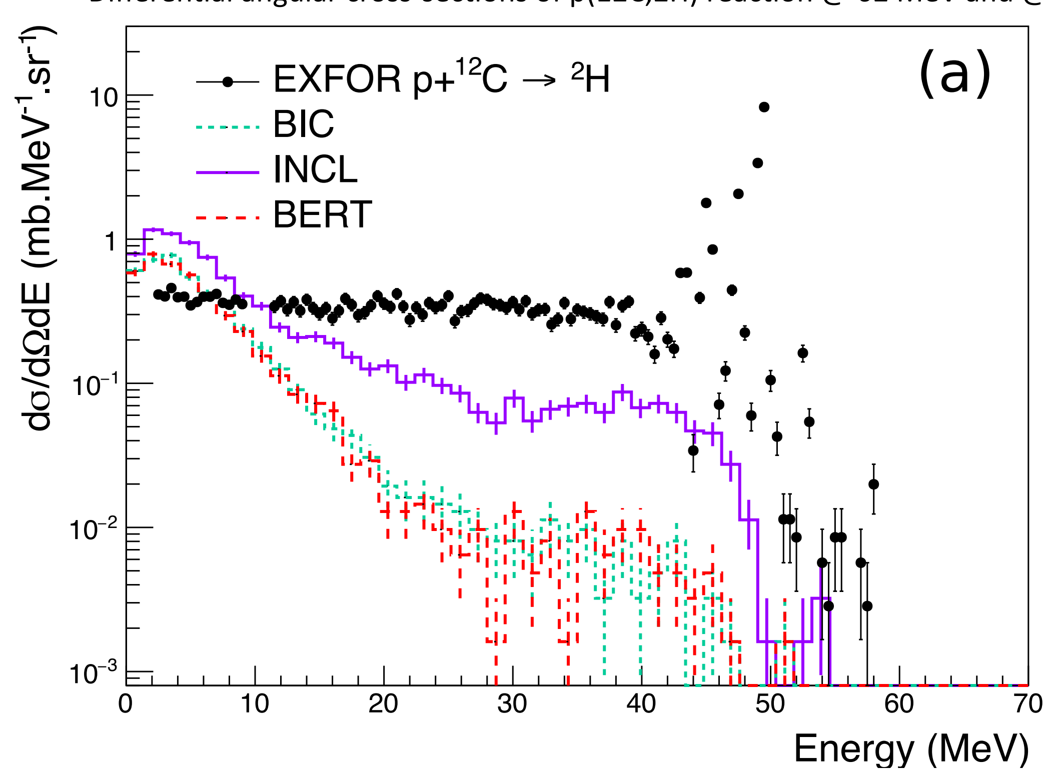
Cross-section measurements (iii)

- Why ?
  - Discrepancies between models:

Charge changing cross-sections of p(27Al,3He)



Differential angular cross-sections of p(12C,2H) reaction @ 62 MeV and @ 25°



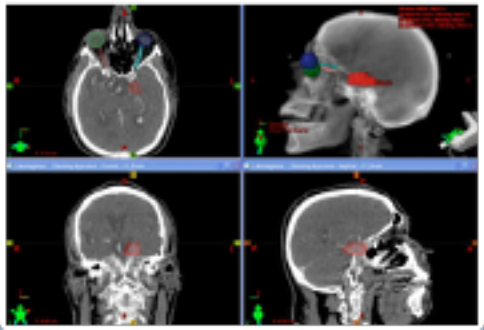
From **Vanstalle**, private communication

➡ No model is better than another …

Cross-section measurements (iv)

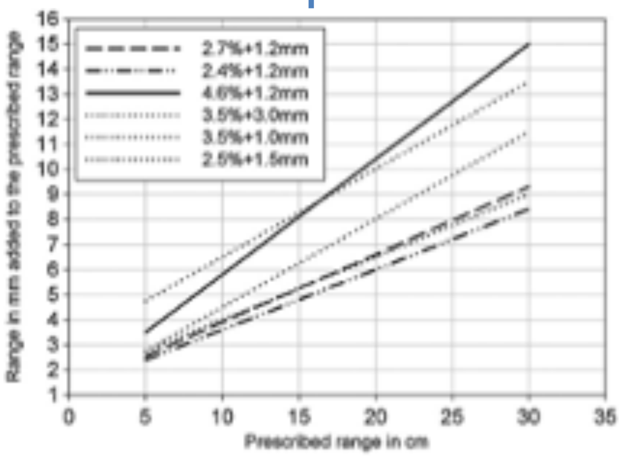
- Why ?
  - Increase TPS accuracy

Imaging
Define tumoral/targeted volume



Treatment planning system (TPS)

Treatment



From **Paganetti**, *"Range uncertainties in proton therapy and the role of Monte Carlo simulations"*, Phys. Med. Biol. (2012).

Dose calculation

Physical processes

Biological processes

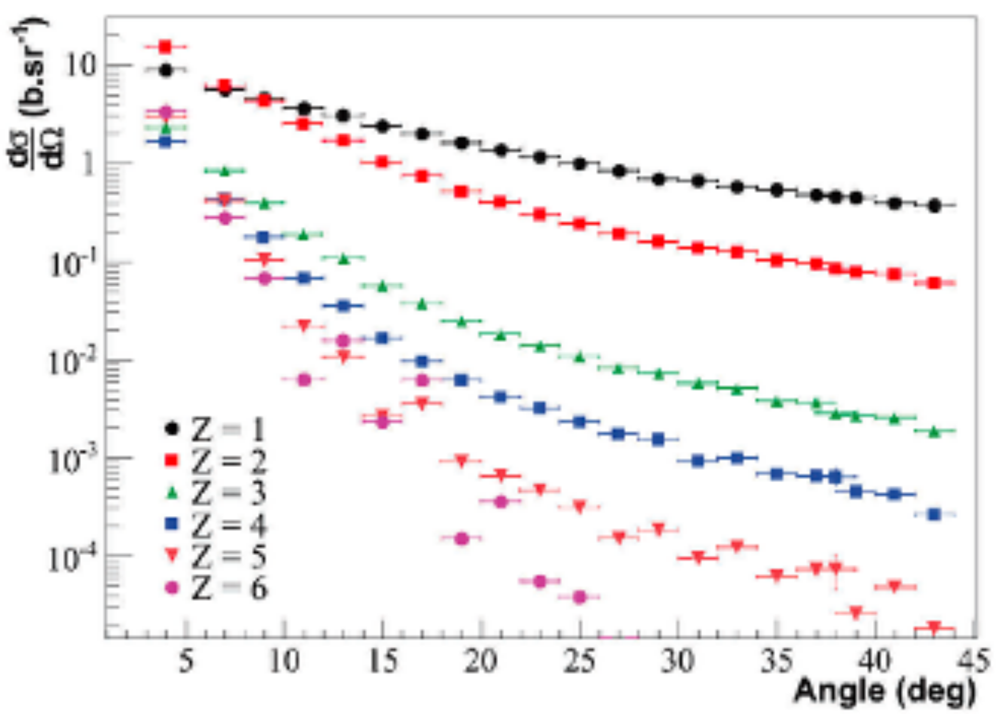
Chemical processes

Irradiation control (PET)

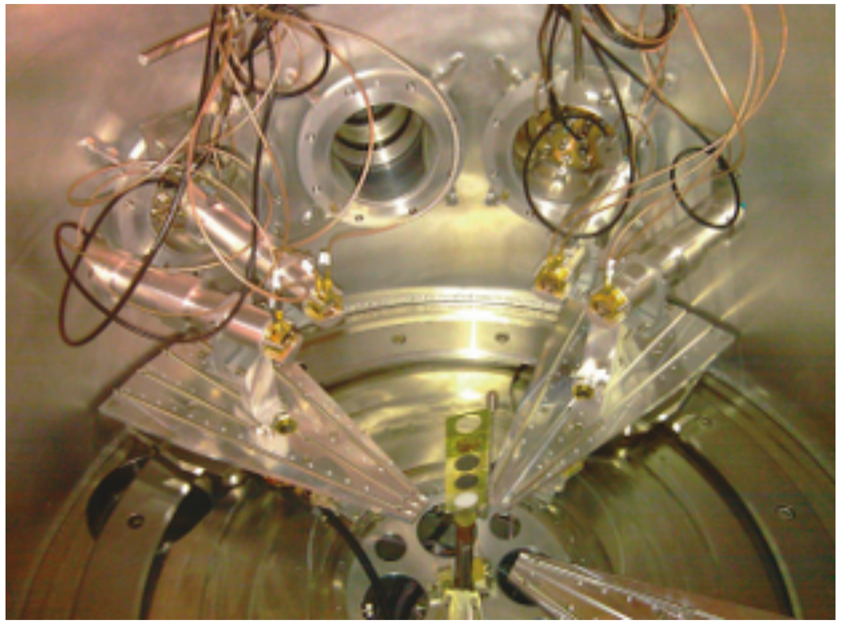
Corrections
Comparison between delivered and planned dose

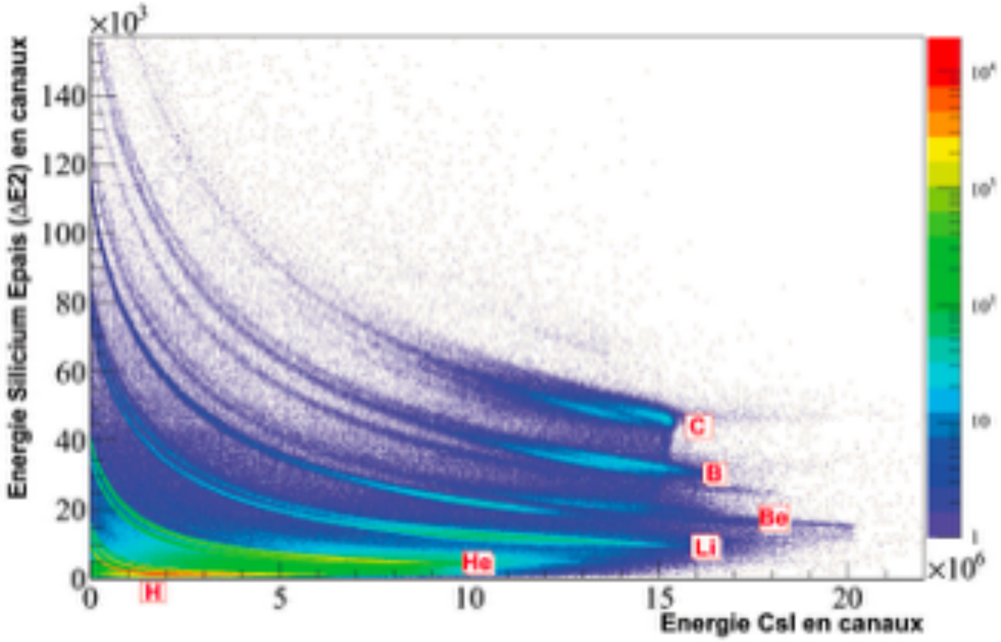
Cross-section measurements (v)

- Examples of former experiments:
  - E600 and E50 @ Ganil:
    - Measurement of secondary particles produced by ^{12}C on C, CH_2, Al, Al_2O_3, Ti and PMMA @ 95 MeV/n and 50 MeV/n



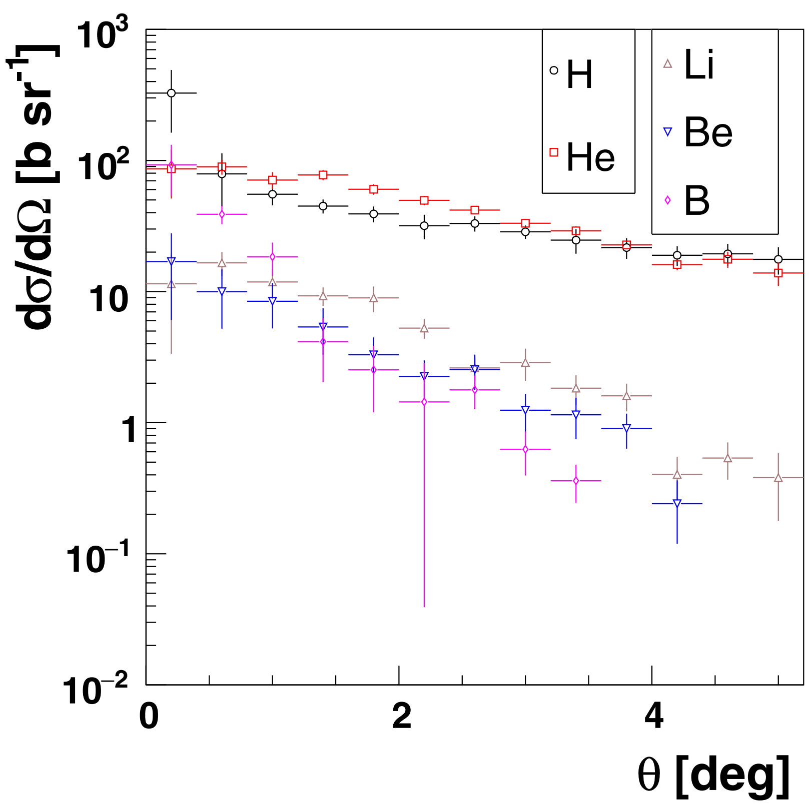
From **D. Juliani** phD, "Etude de la fragmentation lors de la réaction ^{12}C+^{12}C à 95 MeV/n et 400 MeV/n dans la cadre de la hadronthérapie", (2013).



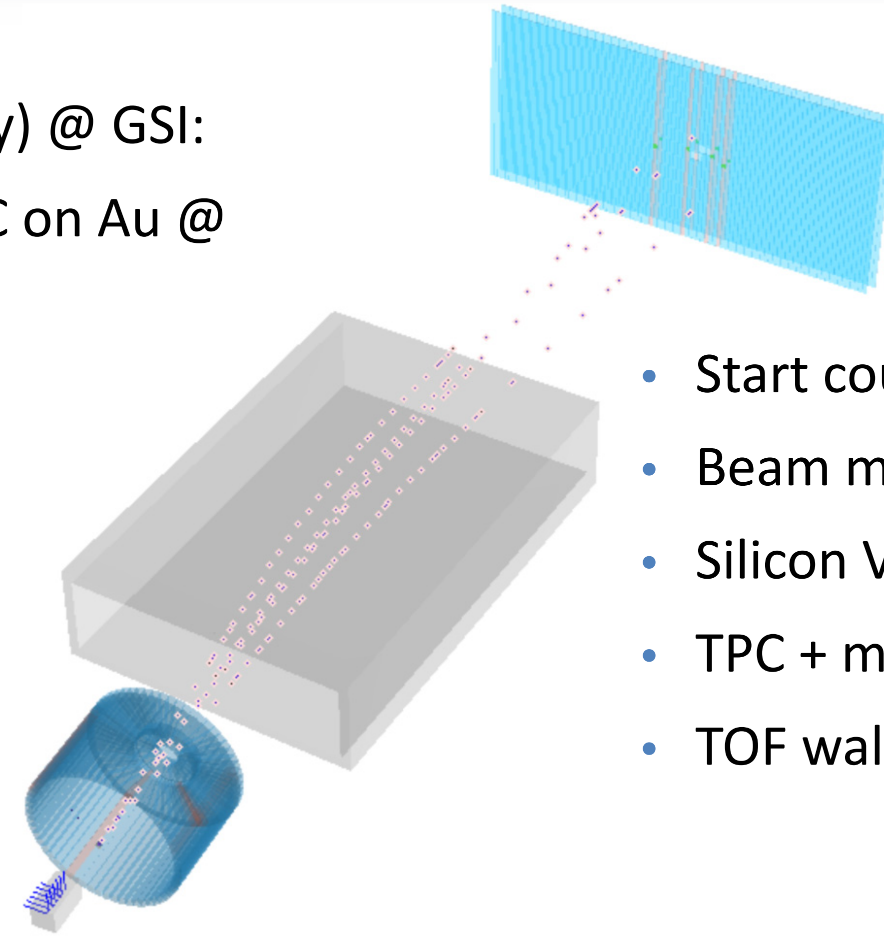


Cross-section measurements (vi)

- Examples of former experiments:
  - FISRT(Fragmentation of Ion for Space and RadioTherapy) @ GSI:
    - Measurement of secondary particles produced by ^{12}C on Au @ 400 MeV/n



From M. Toppi et al., “Measurement of fragmentation cross sections of ^{12}C ions on a thin gold target with the FIRST apparatus”, Phys. Rev. C **93**, (2016) **064601**

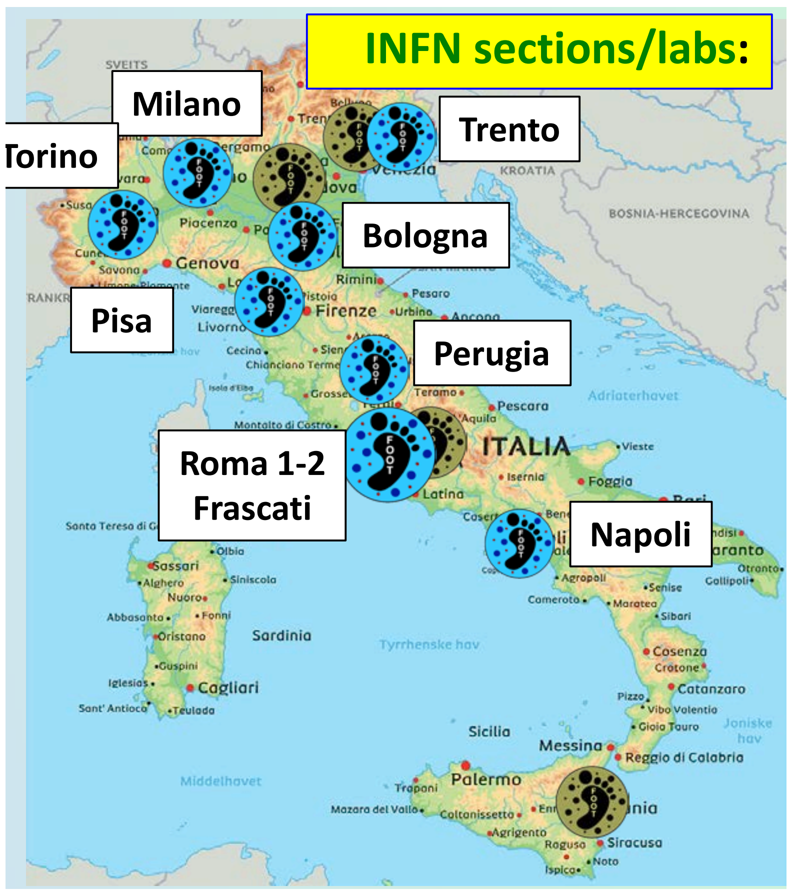


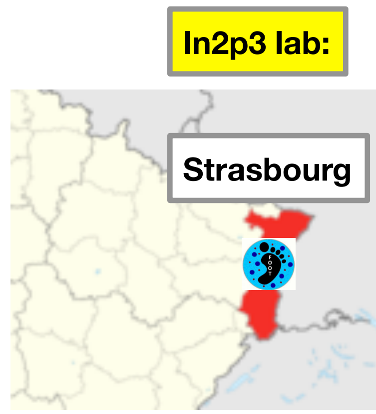
- Start counter
- Beam monitoring
- Silicon Vertex detector
- TPC + magnet
- TOF wall

θ (deg)	^{6}Li $d\sigma/d\Omega$ (b sr^{-1})	^{7}Li $d\sigma/d\Omega$ (b sr^{-1})	^{7}Be $d\sigma/d\Omega$ (b sr^{-1})	^{9,10}Be $d\sigma/d\Omega$ (b sr^{-1})	^{10}B $d\sigma/d\Omega$ (b sr^{-1})	^{11}B $d\sigma/d\Omega$ (b sr^{-1})
0.2(0.2)	5.5 (7.8)	6 (4.7)	5 (6.1)	12 (8.5)	79 (27)	14 (24)
0.6(0.2)	11 (2.7)	5.8 (1.6)	3.8 (2.7)	6.1 (2.9)	24 (3.4)	15 (5.5)
1(0.2)	3.4 (1.4)	8.5 (2.3)	4.5 (2)	3.9 (1.3)	6.2 (2.8)	12 (4.6)
1.4(0.2)	3.2 (1.1)	6.1 (1.1)	3.4 (1.5)	1.9 (0.76)	2.5 (1.6)	1.7 (2.2)
1.8(0.2)	4.8 (1.7)	4.1 (0.69)	1.9 (0.77)	1.4 (0.59)	2 (1.3)	0.51 (0.67)
2.2(0.2)	2.4 (0.6)	2.9 (0.7)	1.6 (0.54)	0.65 (0.28)	0.63 (0.97)	0.81 (0.75)
2.6(0.2)	0.91 (0.4)	1.7 (0.44)	1.9 (0.56)	0.69 (0.31)	1.1 (0.42)	0.67 (0.32)
3(0.2)	1.7 (0.73)	1.2 (0.32)	1.1 (0.28)	0.16 (0.21)	0.41 (0.18)	0.22 (0.19)
3.4(0.2)	1.1 (0.37)	0.74 (0.26)	0.89 (0.28)	0.26 (0.16)	0.098 (0.071)	0.26 (0.11)
3.8(0.2)	1.4 (0.45)	0.19 (0.35)	0.72 (0.21)	0.19 (0.1)		
4.2(0.2)	0.3 (0.18)	0.1 (0.23)	0.23 (0.11)	0.0076 (0.038)		
4.6(0.2)	0.41 (0.18)	0.13 (0.16)				
5(0.2)	0.34 (0.16)	0.046 (0.099)				

FOOT experiment (i)

- FOOT: FragmentatiOn Of Target
  - International collaboration (biggest) in X-section measurements



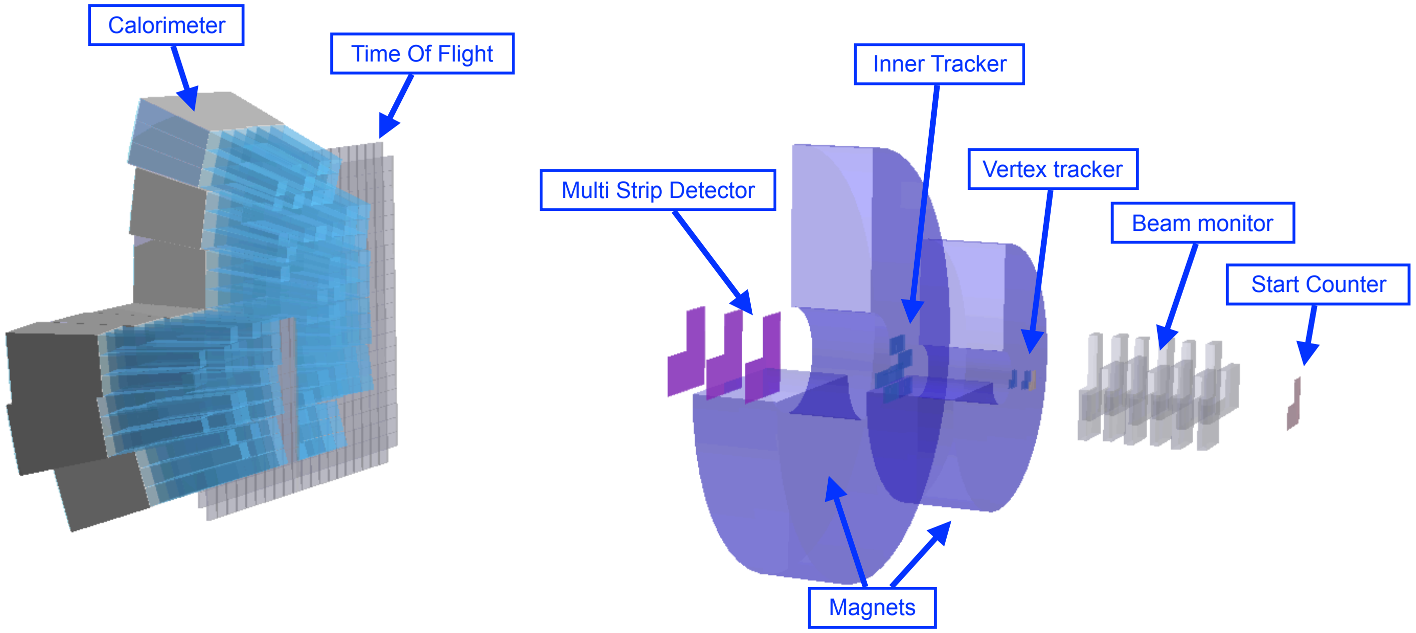


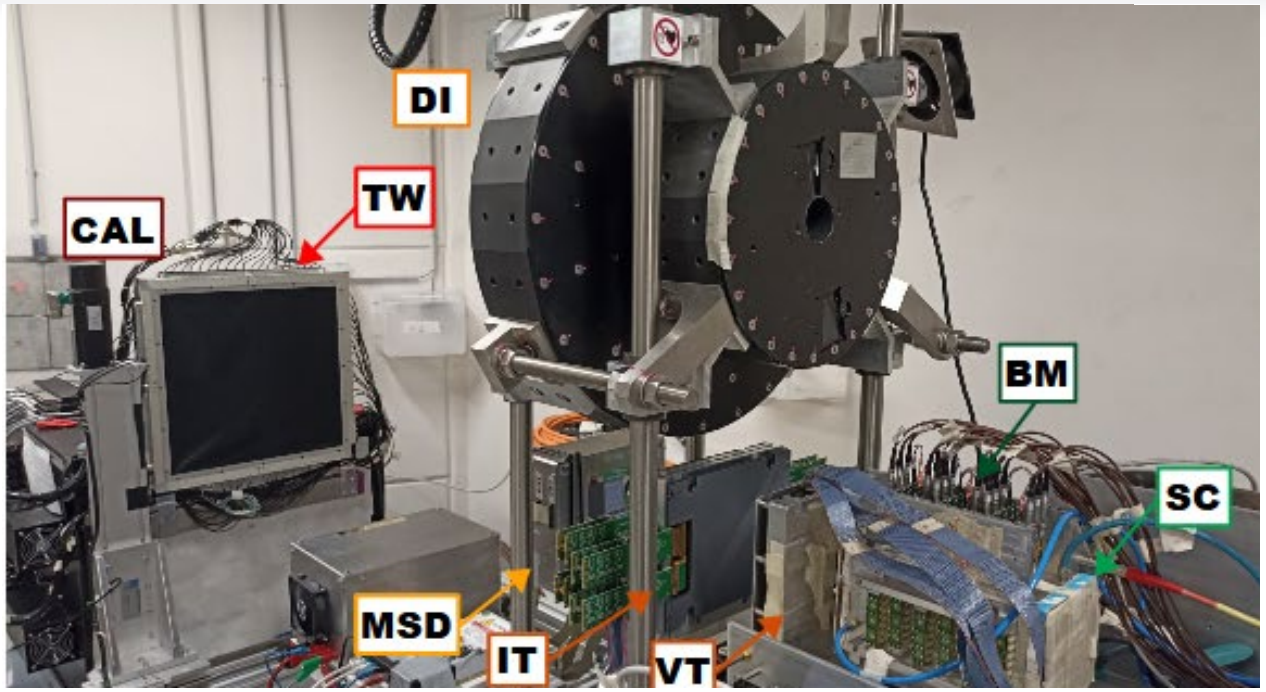
- 9 INFN Laboratories
- 2 (+2) Facilities: CNAO, GSI, (Frascati, Trento)
- 12 Italian University
- 1 (+1) foreign Instituts: Strasbourg-Alsace, (Calicut-India)

➡ ~80 members

FOOT experiment (ii)

- Electronic Setup
  - Tracking system: BM+VTX+ITR+MSD
  - Downstream: TW & CAL





- Mass spectrometer

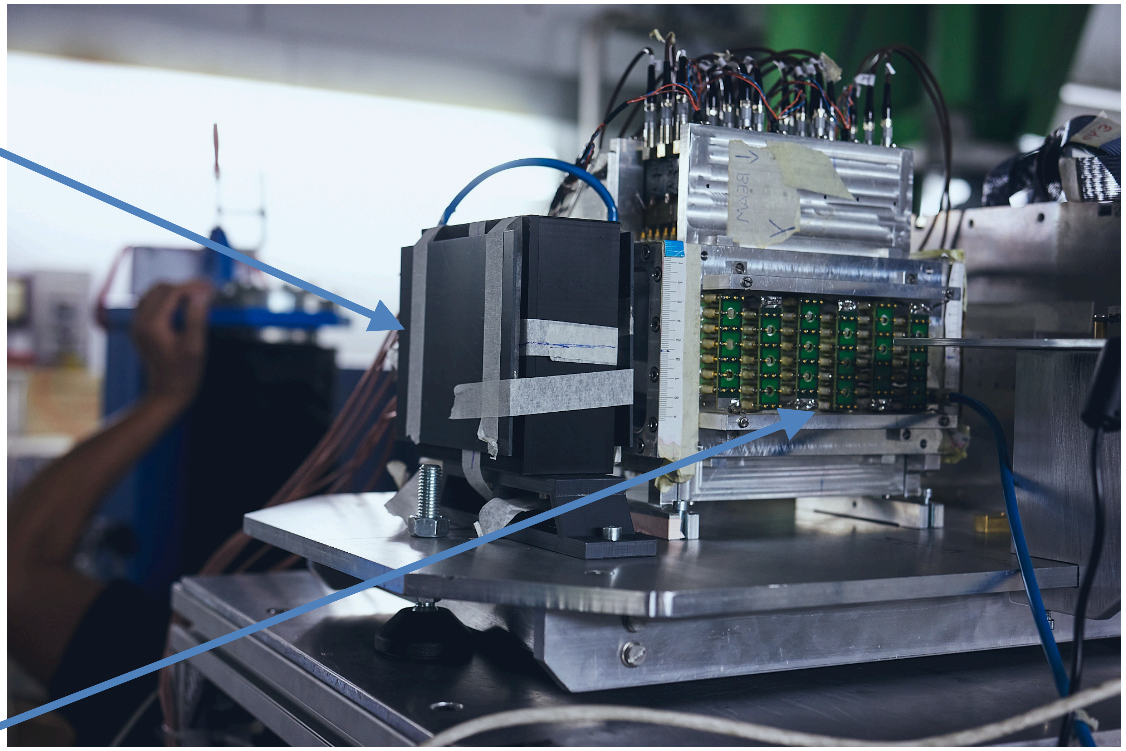
$$\frac{d\vec{p}}{dt} = q\vec{\beta}c \times \vec{B}$$
$$p = \gamma\beta mc$$

$$E_{kin} = mc^2(\gamma - 1)$$
$$\beta = \frac{L}{ToF}\frac{1}{c}$$

- Required performances:
  - $\sigma(p)/p < 5\,\%$
  - $\sigma(\Delta E)/E < 5\,\%$
  - $\sigma(ToF)/ToF < 100\,ps$

FOOT experiment (iii)

- Interaction region
  - Start counter:
    - 250 μm EJ-228
    - 6 SiPM's
    - Efficiency > 99 %
    - Resolution: < 70 μm

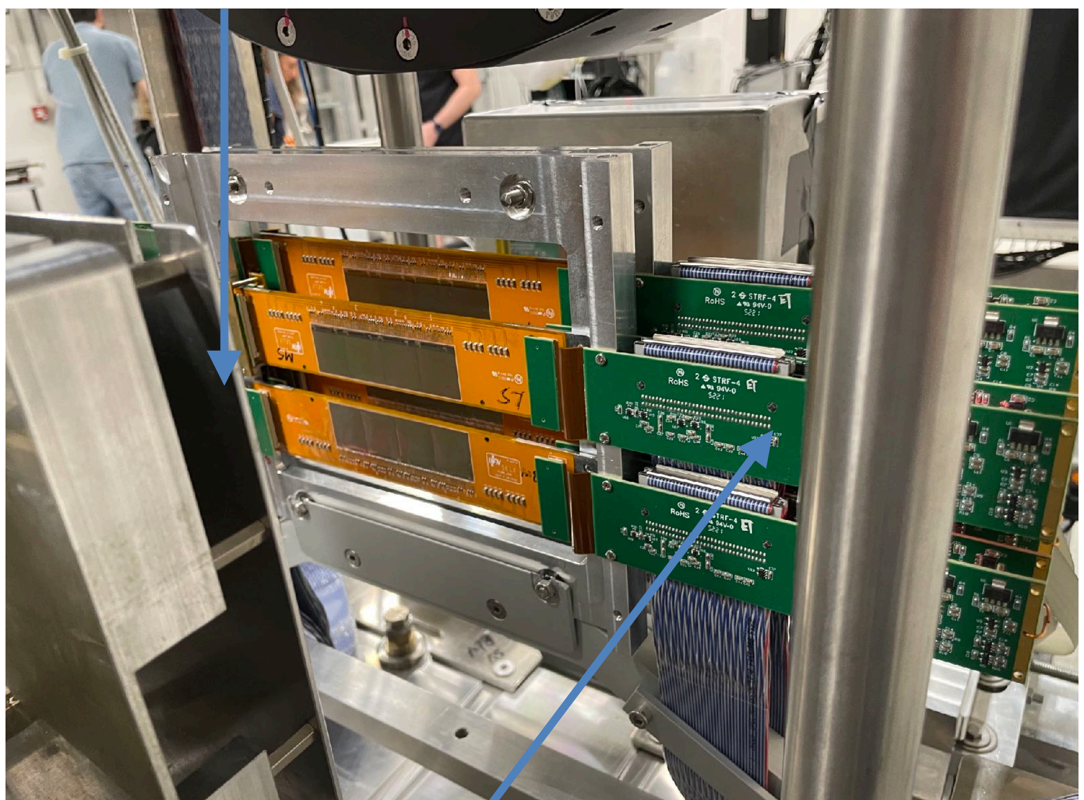


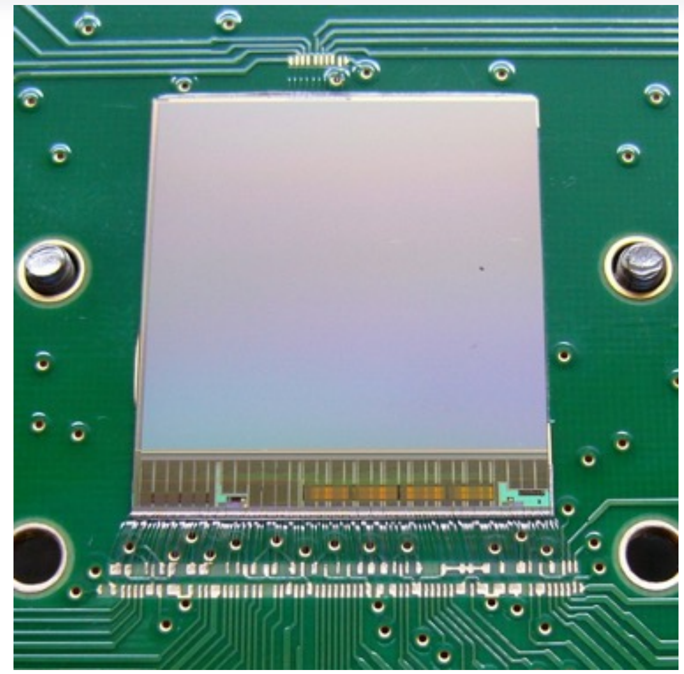
  - Beam monitor:
    - Size: 4x4x13 cm^3
    - TDC readout
    - Gas mixture: Ar (80%) + CO_2 (20%)
    - Efficiency > 90 %
    - Resolution: < 150 μm

Y. Dong et al, *The Drift Chamber detector of the FOOT experiment: Performance analysis and external calibration*, NIM A **986 (2021) 164786**

FOOT experiment (iv)

- Interaction region (ii)
  - Vertex:
    - Size: 2x2 cm^2
    - 4 planes of M28





- MAPS (AMS 350 nm)
- Thickness: 50 µm, 14 µm epi-layer
- 928 (rows) x 960 (columns) pixels
- Pitch: 20.7 µm
- Size: 20.22 mm x 22.71 mm
- Chip readout time: 185.6 µs
- Digital ouput

- Inner tracker:
  - Size: 8x8 cm^2
  - 32 M28 sensors over 2 planes

R. Rescigno, Ch. Finck, D. Juliani, et al.,
Performance of the reconstruction algorithms of the FIRST experiment Pixel Sensors Vertex detector
Nucl. Instrum. Methods Phys. Res. A **767** (2014) **34**

E. Spiriti, Ch. Finck et al., *CMOS active pixel sensors response to low energy light ions*
Nucl. Instrum. Methods Phys. Res. A **875**, (2017) **35**

C.-A. Reidel, Ch. Finck, et al., *Alignment algorithm for silicon pixel detector for ion-beam therapy application*
Nucl. Instrum. Methods Phys. Res. A **931**, (2019) **142**

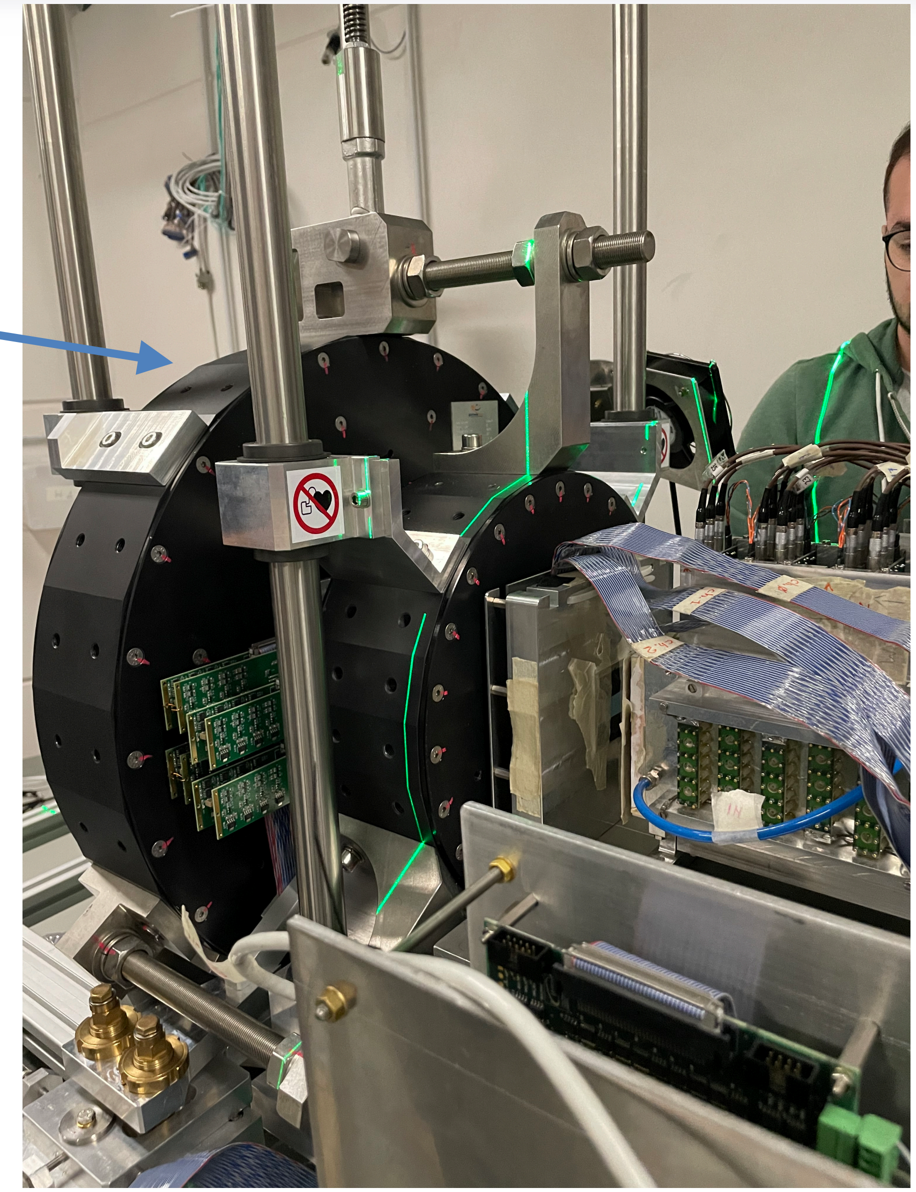
C.-A. Reidel, C. Schuy, Ch. Finck, et al., *Response of the Mimosa-28 pixel sensor to a wide range of ion species and energies*
Nucl. Instrum. Methods Phys. Res. A **1017** (2021) **165807**

FOOT experiment (v)

❑ Interaction region (iii)

- Magnet:
  - 2 permanent magnets
  - Value: 1.4 and 0.9 T at center
  - Material: SmCo

A. Trigilio et al., Characterization of a Permanent Magnetic Dipolar System for the FOOT Experiment
Journal of Instrumentation **20** (2025) **T09010**

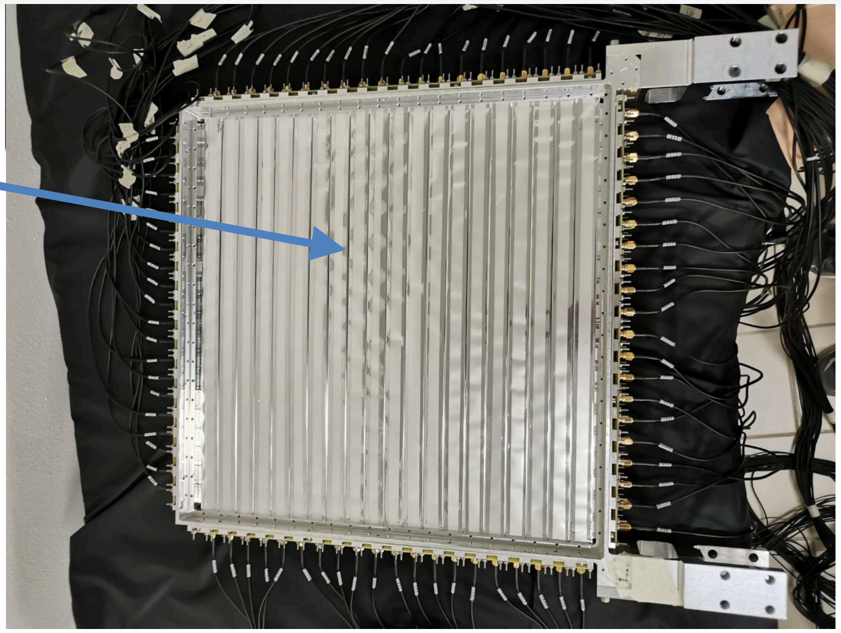


- Micro strip detector:
  - 6 layers single sided strips
  - 762 strips
  - Size: 7x9 cm^2
  - Pitch: 150 μm
  - Resolution: < 50 μm

G. Silvestre at al., *Characterization of 150 μm thick silicon microstrip prototype for the FOOT experiment*
Journal of Instrumentation **17**(12) (2022)

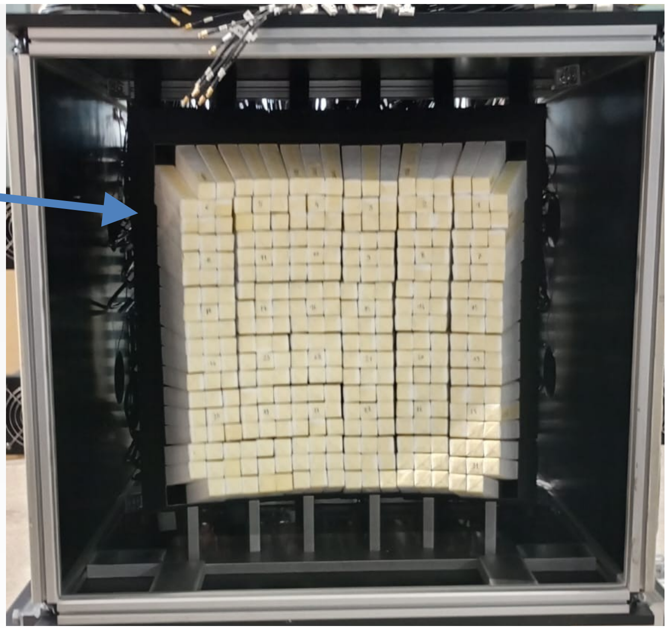
FOOT experiment (vi)

- Downstream region
  - Time of flight:
    - 20 bars of 2x44 cm^2 EJ-200
    - Size: 40x40 cm^2
    - 320 SiPM's readout
    - Resolution: < 50 ps



M. Morrocchi et al., *Development and characterization of a ΔE-TOF detector prototype for the FOOT experiment* Nucl. Instrum. Methods Phys. Res. A **911** (2018) **1**

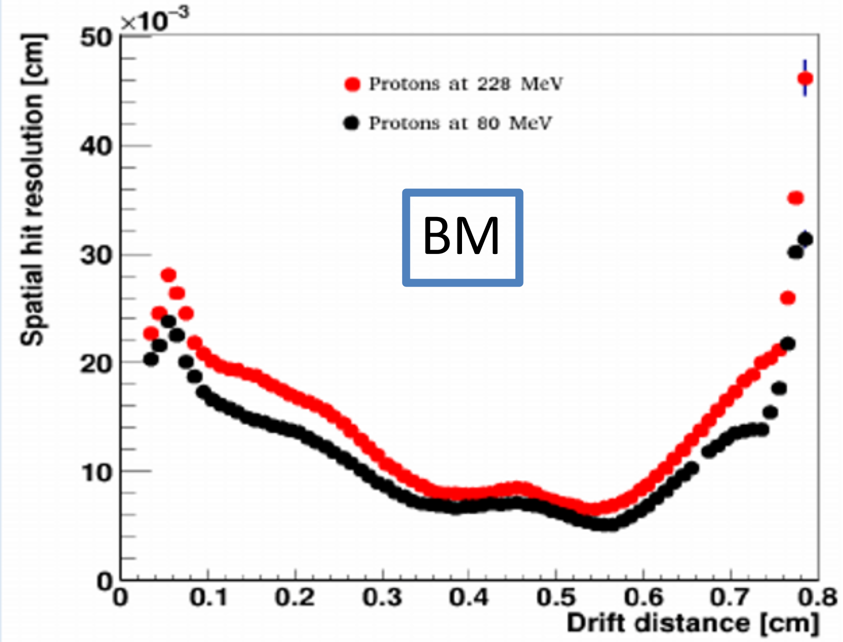
- Calorimeter:
  - 320 crystals of 2x2x240 cm3
  - 25 SiPM's readout per crystal
  - Resolution: < 4-5 %

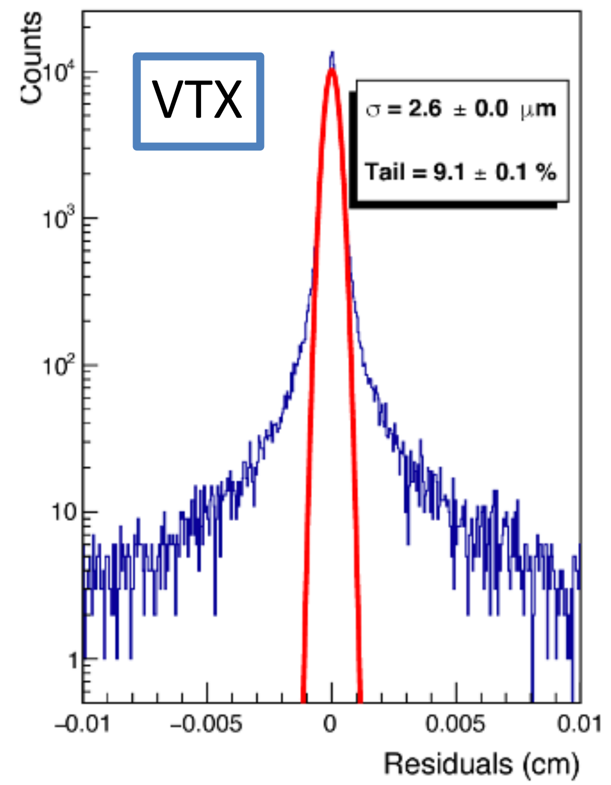


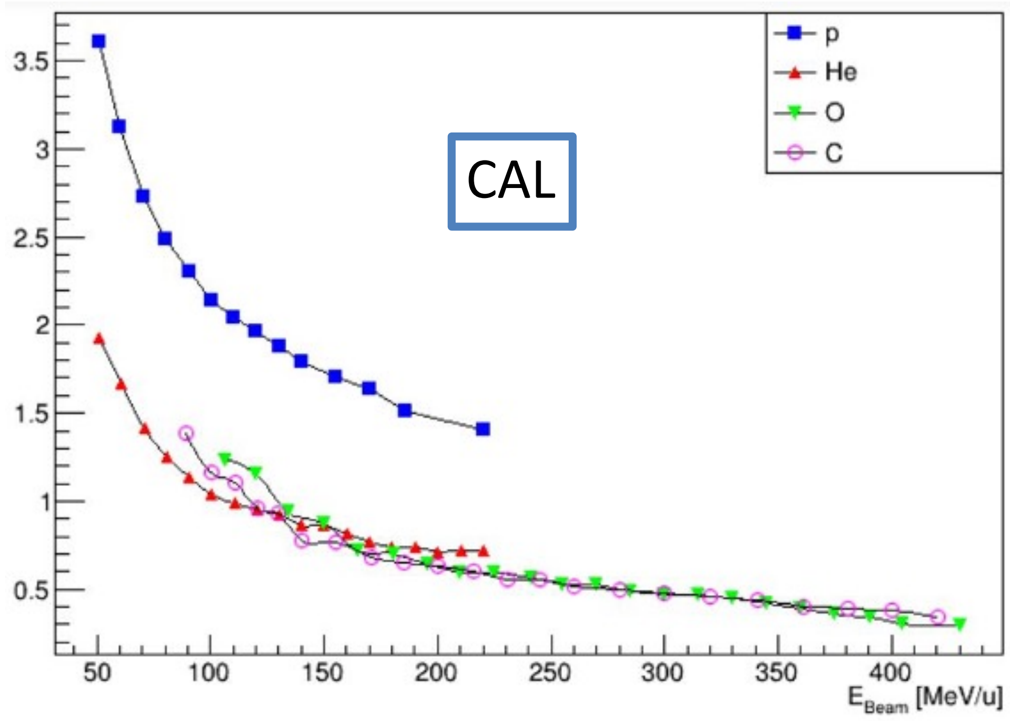
N. Bartosik et al., *Development and Performance Assessment of the Calorimeter Module for the FOOT experiment* Journal of Instrumentation, **20**, (2025) **P0302**

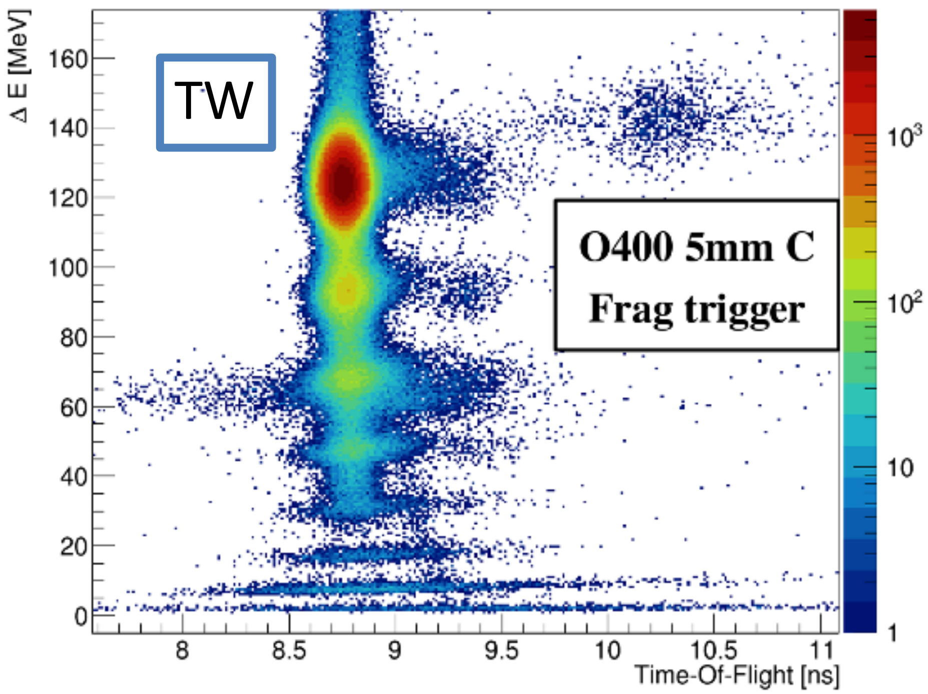
FOOT experiment (vii)

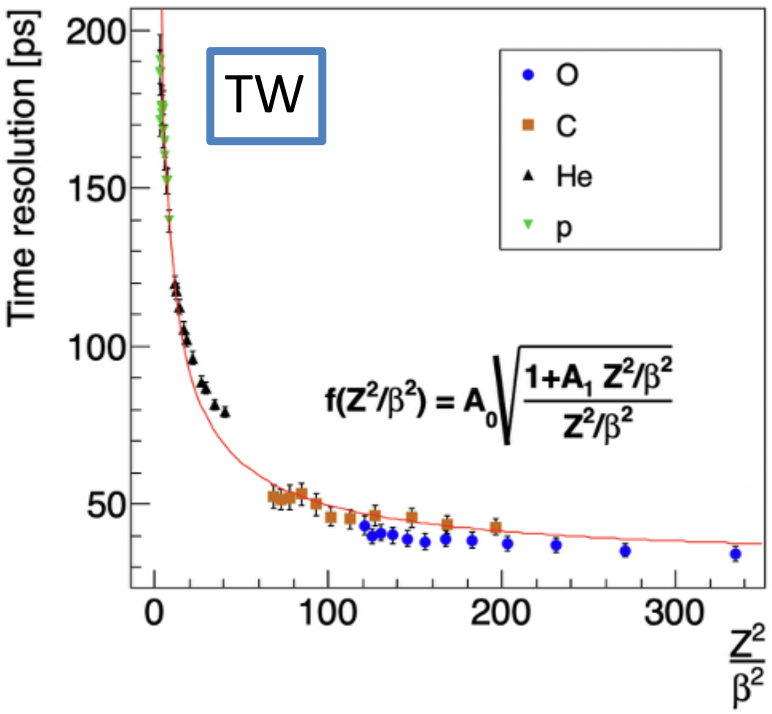
- FOOT performances











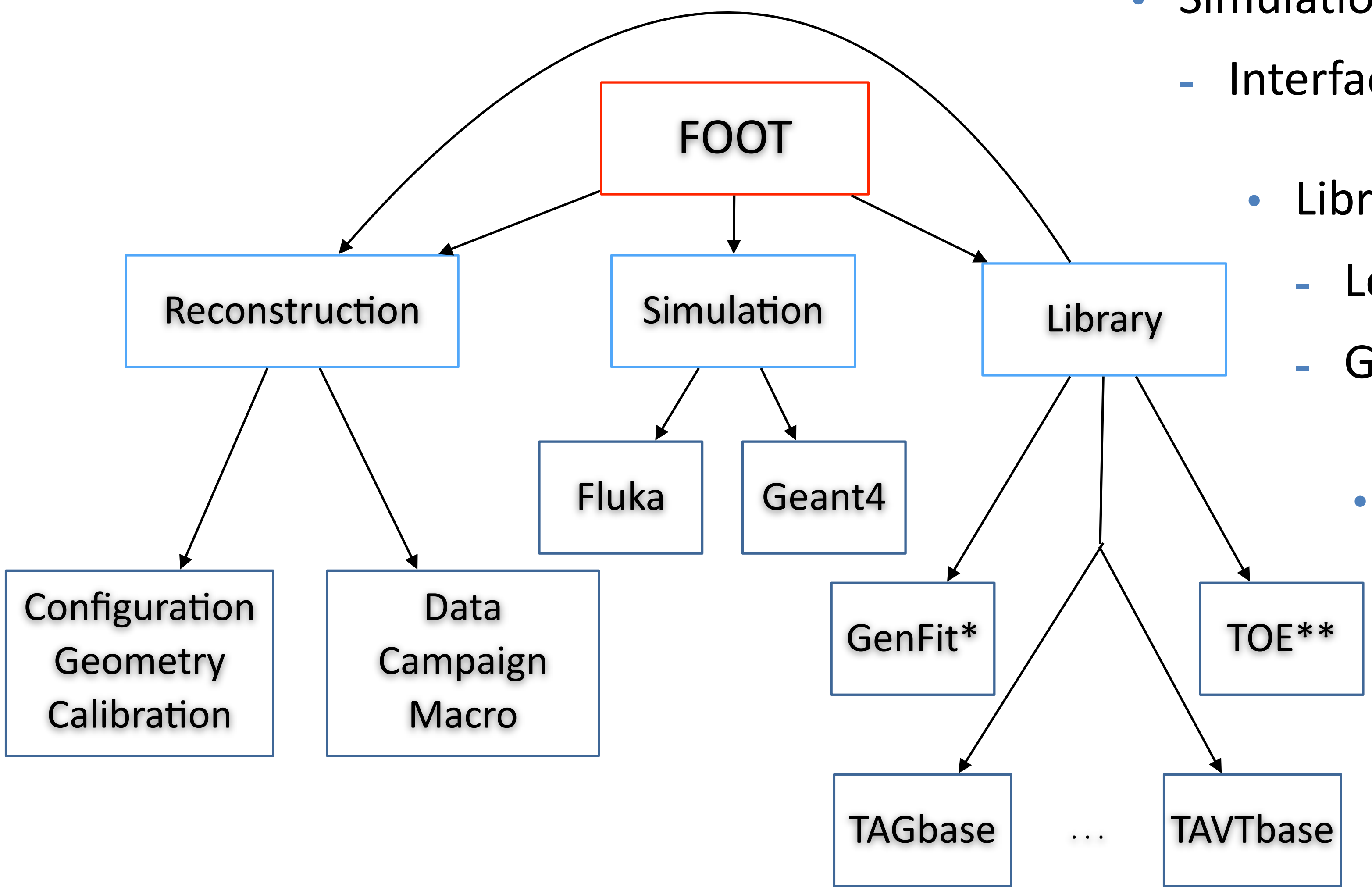
FOOT performances:

- ✓ $\sigma(E_{kin})/E_{kin} < 3\%$
- ✓ $\sigma(\Delta E)/\Delta E \sim 4\text{-}5\%$
- ✓ $\sigma(TOF) > 50$ ps
- ✓ $\sigma(p)/p < 5\%$

➡ Fulfilled requirements

SHOE (Software for Hadrontherapy Optimisation Experiment)

❑ Code architecture



- Simulation[1]:
  - Interface Fluka or Geant4 toolkit
- Library:
  - Local reconstruction (hit, cluster, track & vertices)
  - Global reconstruction: GenFit[2] or TOE[3] package
- Reconstruction:
  - Configuration, geometry and calibration files
  - Data for magnetic field
  - Campaign and run file storage
- Managers:
  - Reconstruction manager
  - Campaign manager
  - Run manager
  - Name manager

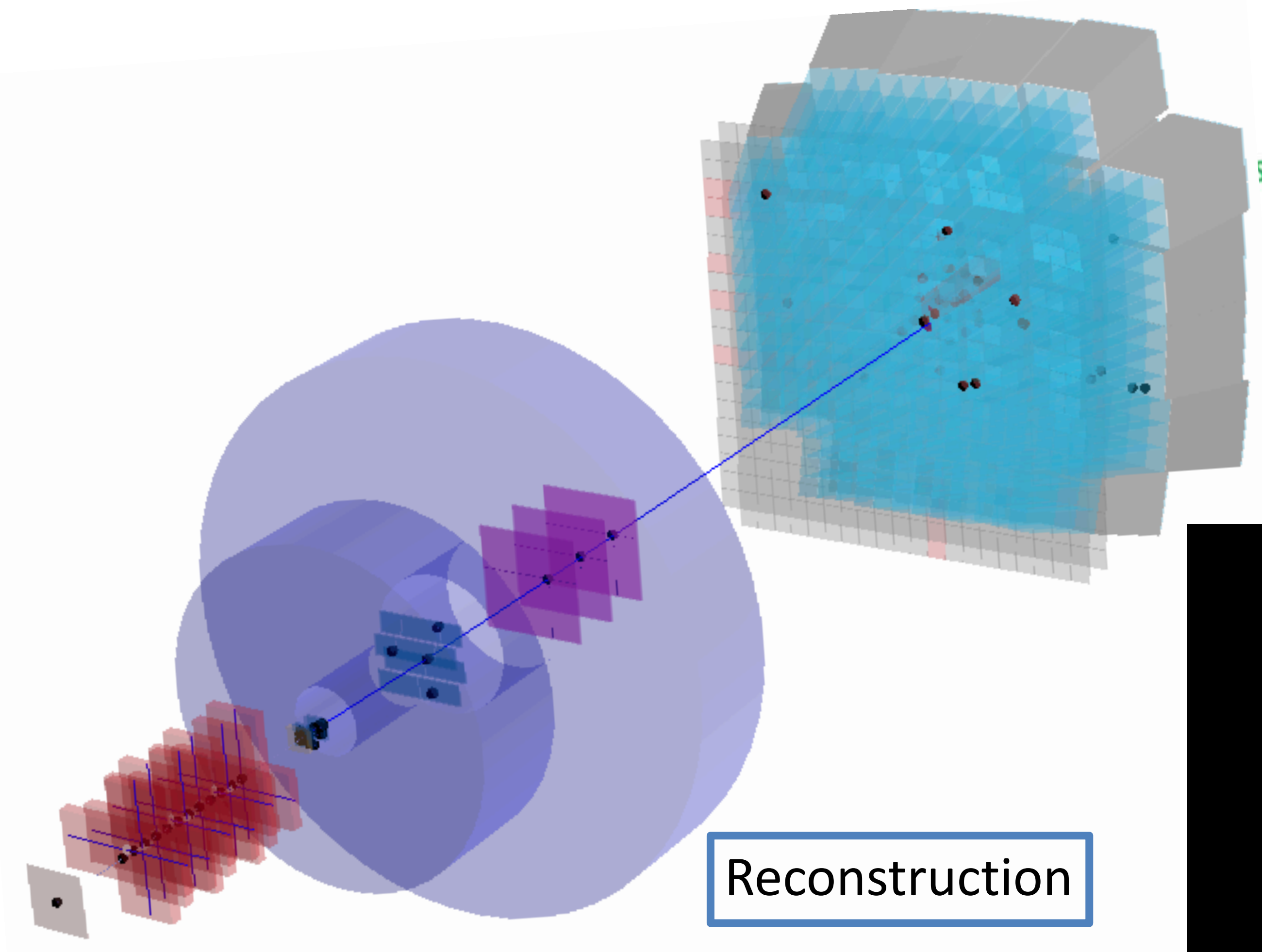
[1]Y. Dong, S.M. Valle, G. Battistoni, I. Mattei, Ch. Finck, et al.,
The FLUKA Monte Carlo simulation of the magnetic spectrometer of the FOOT experiment
Comput. Phys. Commun. **307** (2025) **109398**

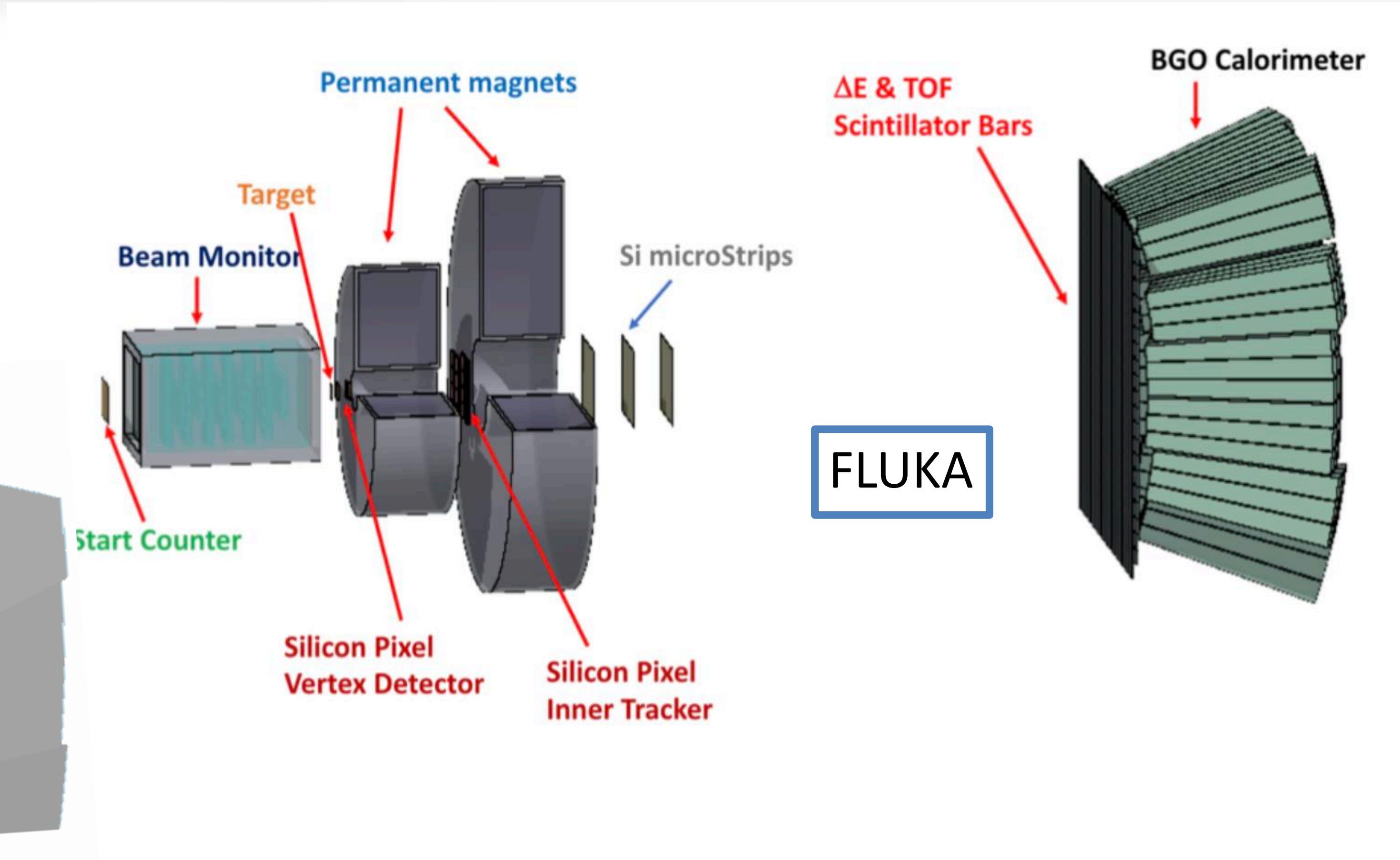
[2]Generic Track Reconstruction Toolkit
Ch. Höppner et al., Technische Universität München, Physik-Department

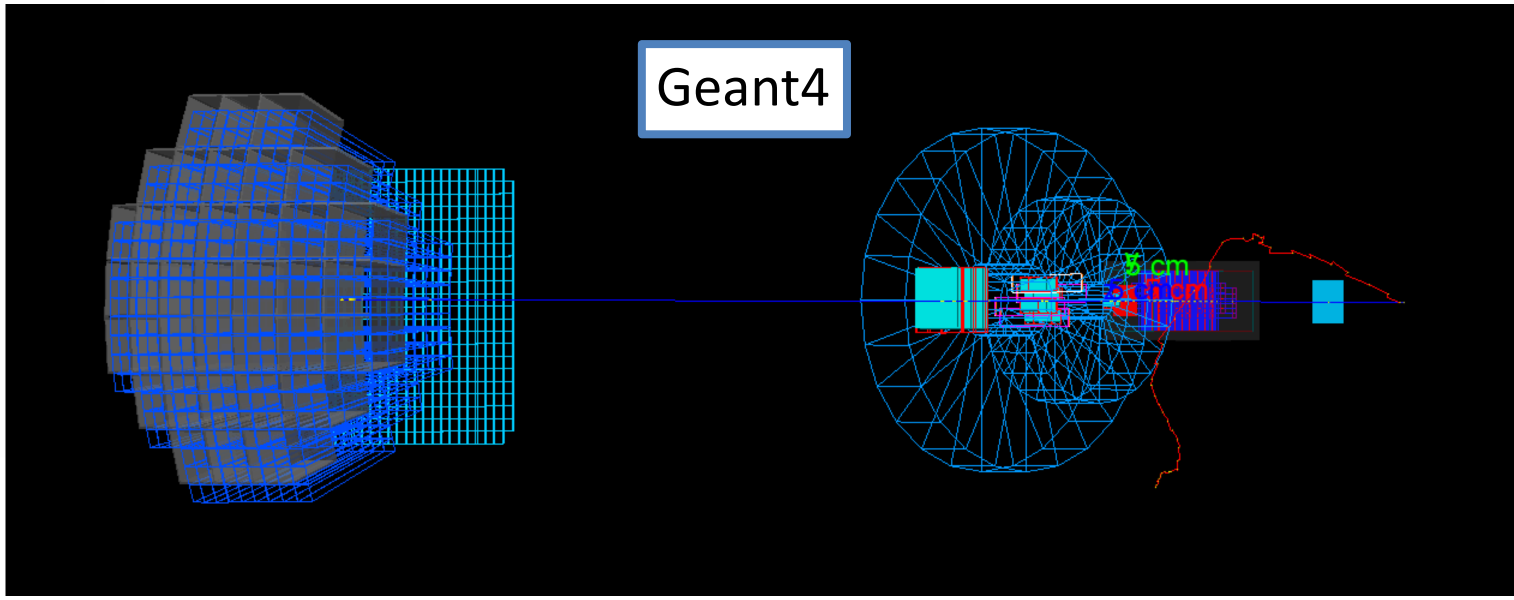
[3]TOE: Tracking Of Ejectile own developed global reconstruction tool

SHOE (Software for Hadrontherapy Optimisation Experiment)

- Geometries:
  - Common geometries for simulation & reconstruction







➡ Don't need to load simulation libraries to retrieve geometry objects

Campaigns

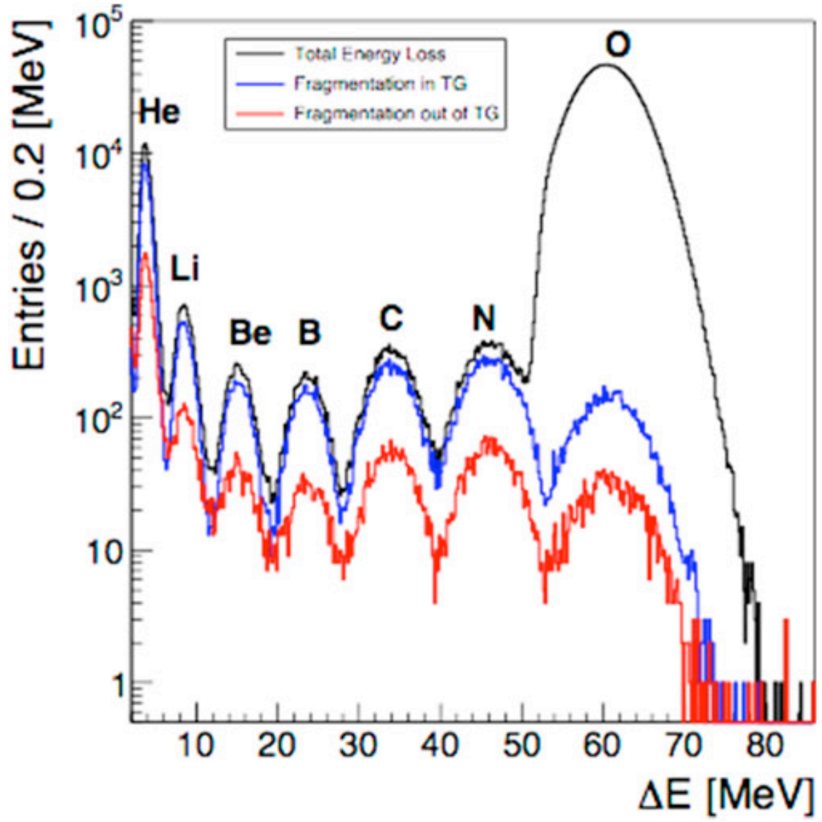
- Table:

Electronic setup		
Campaign	Beams Energy [MeV/u] / Targets	Detectors
GSI 2019	^{16}O @ 400 on ^{12}C	SC, BM, TW
GSI 2021	^{16}O @ 200, 400 on ^{12}C, C_2H_4	SC, BM, VTX, MSD, TW
HIT 2022C	He @ 100, 140, 200, 220	SC, BM, MSD, TW, CAL
CNAO 2022	^{12}C @ 200 on ^{12}C	SC, BM, VTX, MSD, TW, CAL
CNAO 2023	^{12}C @ 200 on ^{12}C, C_2H_4	SC, BM, VTX, ITR, MSD, TW, CAL + Mag
CNAO 2024	^{12}C @ 200 on ^{12}C	SC, BM, VTX, ITR, MSD, TW, CAL + Mag
CNAO 2025	^{12}C @ 200 on ^{12}C	SC, BM, VTX, ITR, MSD, TW, CAL SC, BM, VTX, ITR, MSD, TW, CAL + Mag

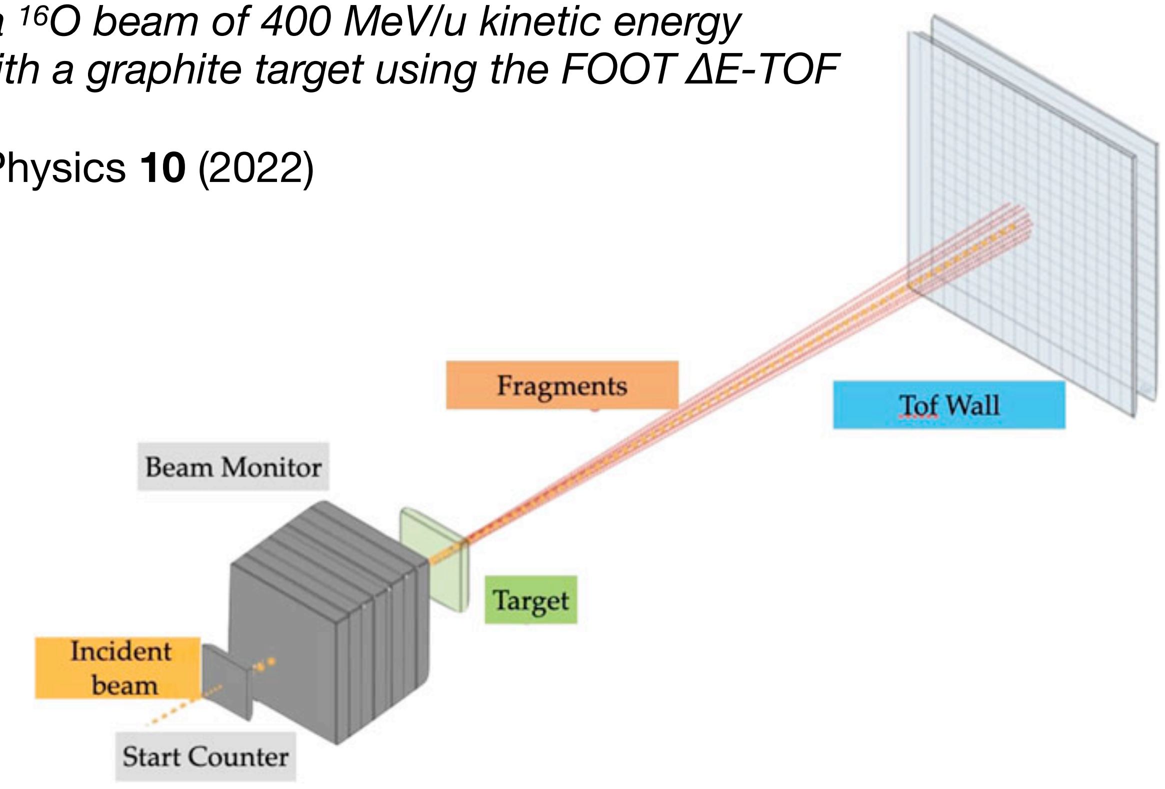
➡ Many campaigns with different stages of setup

Results (i)

- GSI2019:
  - $^{16}O \rightarrow {}^{12}C$ (5mm) @ 400 MeV/u



M. Toppi, A. Sarti, et al., *Elemental fragmentation cross sections for a ^{16}O beam of 400 MeV/u kinetic energy interacting with a graphite target using the FOOT ΔE-TOF detectors*
Frontiers of Physics **10** (2022)

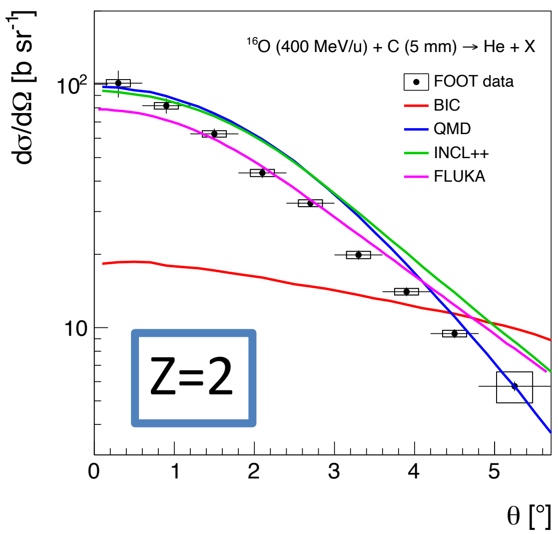


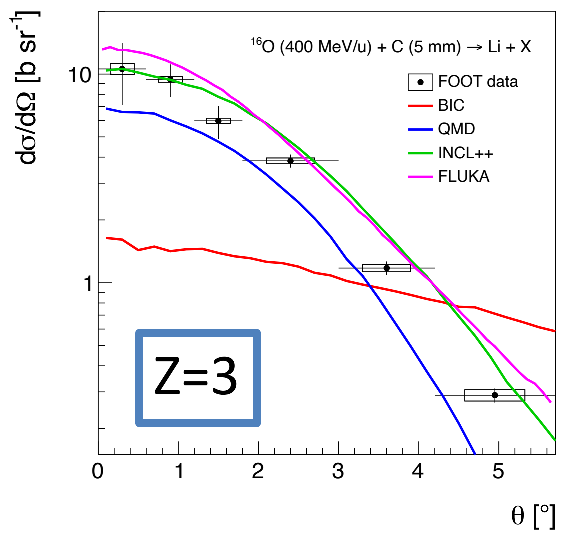
Element	$\sigma_{frag} \pm\Delta_{stat} \pm\Delta_{sys}$ [mbarn]	$\Delta_{stat}/\sigma_{frag}$	$\Delta_{sys}/\sigma_{frag}$	σ_{MC} [mbarn]
He	789 ± 35 ± 67	4.4%	8.5%	705 ± 2
Li	101 ± 13 ± 10	12.5%	10.4%	74.9 ± 0.6
Be	33 ± 9 ± 3	26%	10.3%	37.5 ± 0.4
B	78 ± 11 ± 6	14%	8.5%	41.8 ± 0.4
C	131 ± 14 ± 4	11%	2.8%	87.7 ± 0.6
N	117 ± 14 ± 6	12%	4.8%	110.3 ± 0.7

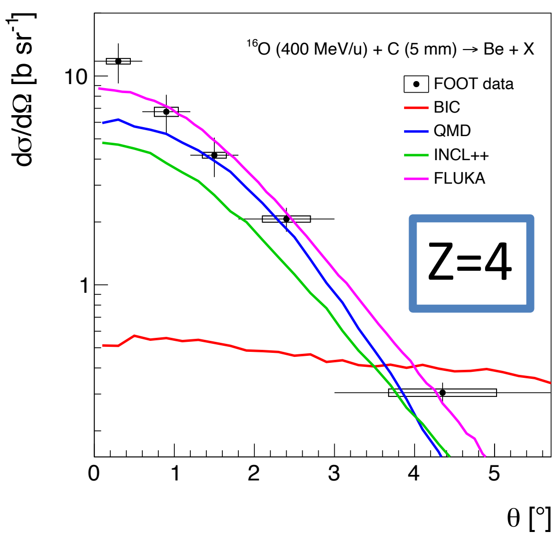
➡ Charge changing cross-section compared with FLUKA MC data

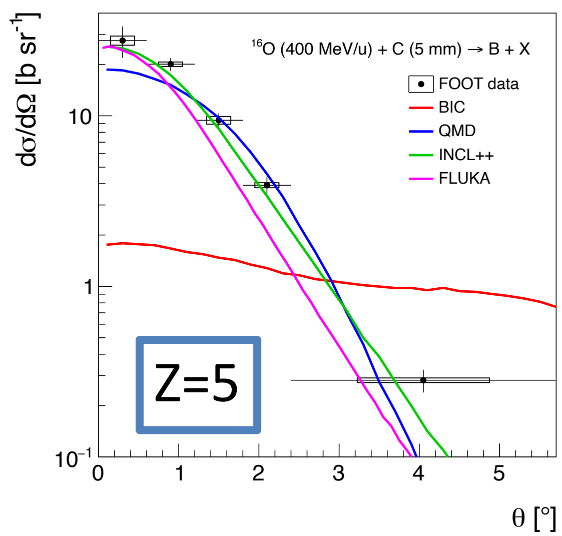
Results (ii)

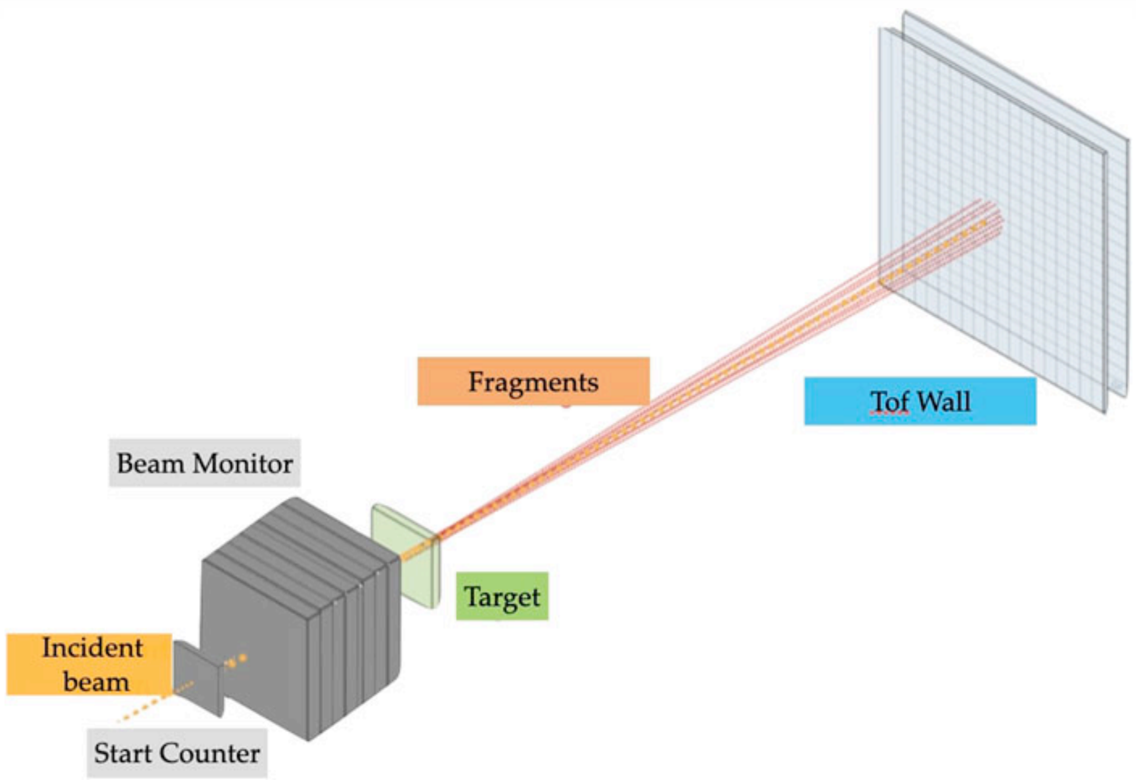
- GSI2021:
  - $^{16}O \rightarrow {}^{12}C$ (5mm) @ 400 MeV/u

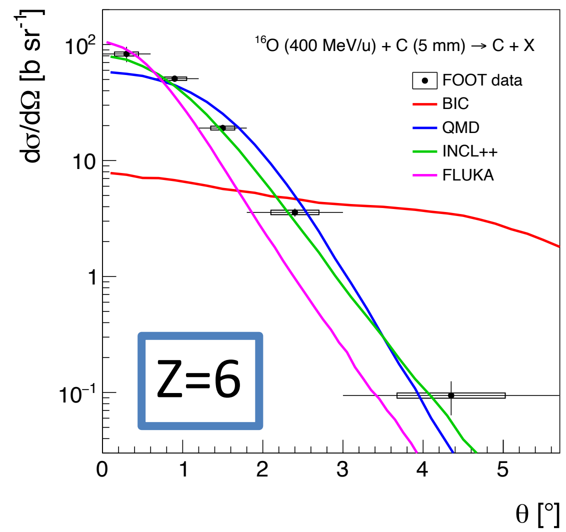


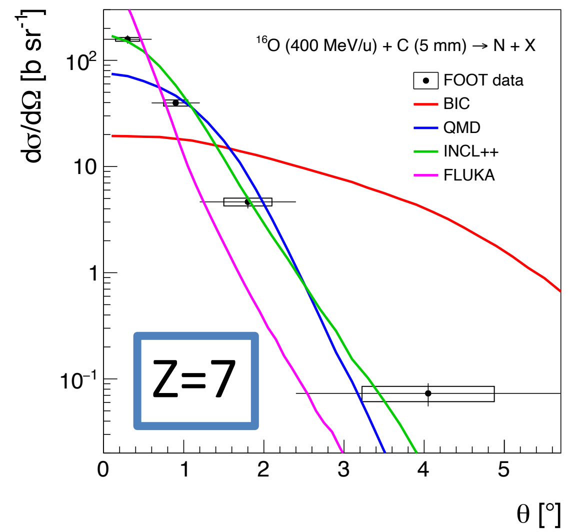










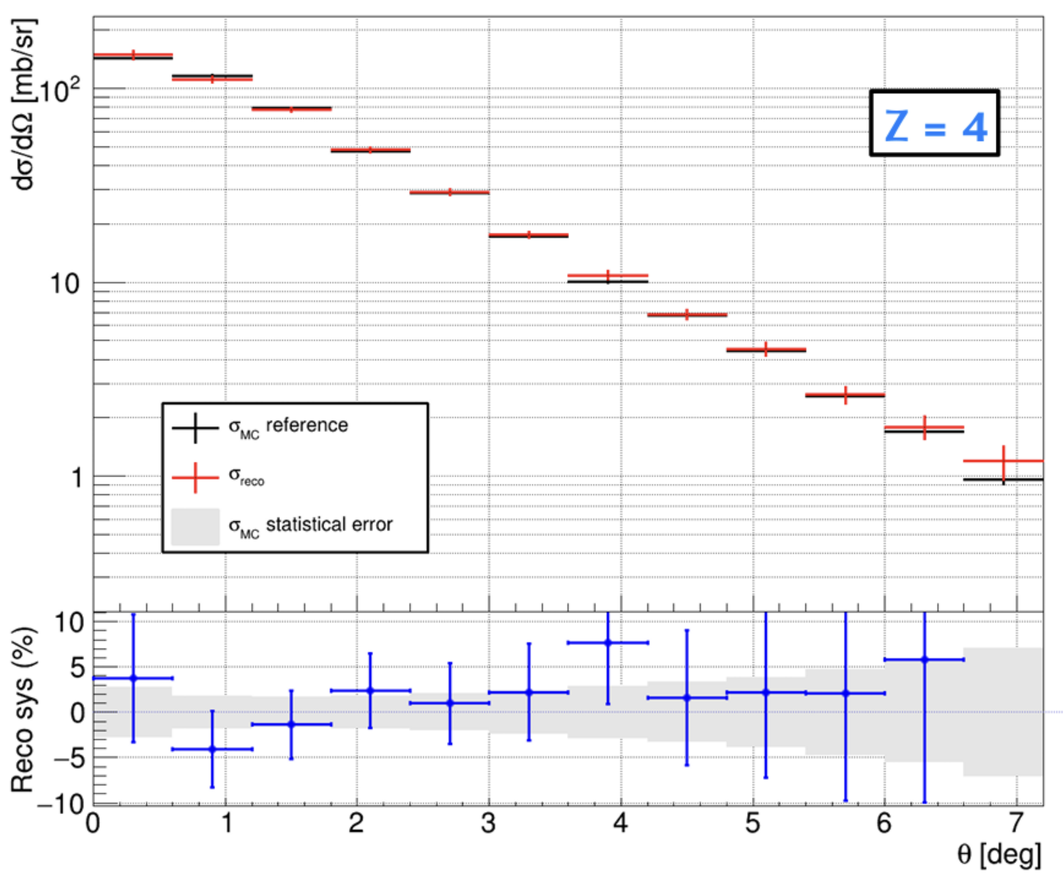


R. Ridolfi, M. Toppi, A. Mengarelli, M. Dondi et al.,
Angular differential and elemental fragmentation cross sections of a 400 MeV/nucleon ^{16}O beam on a graphite target with the FOOT experiment
Phys. Rev. C **112**, (2025) **014610**

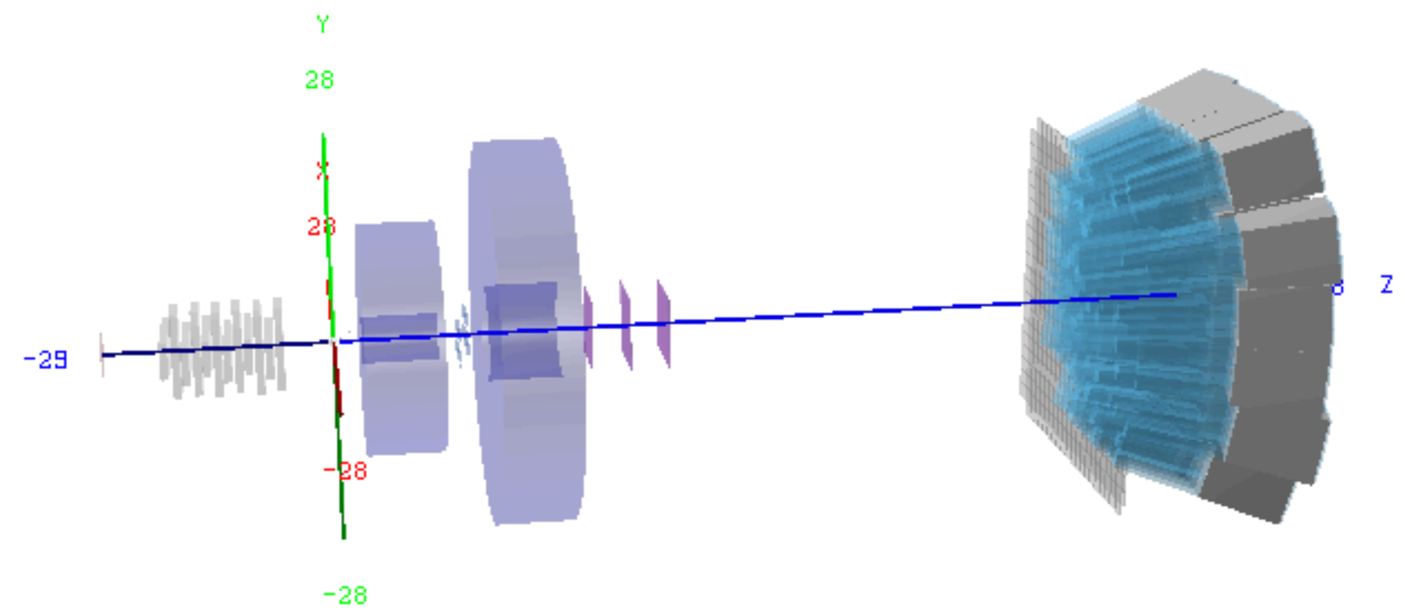
➡ None of the MC models reproduced data

Results (iii)

- Ongoing analysis: (CNAO2023-24 and 25)
  - $^{12}C \rightarrow {}^{12}C$ (5mm) @ 200 MeV/u



R. Zarella, private communication



➡ Still many work to do

Outlooks

- Foreseen experiments:

Beam	Target	Energy MeV/u	Integral Differential elemental	Integral Differential isotopic	Campaign
C	C, C2H4, Al	700 -1500	Angle Energy	YES	GSI 2026/27
C	C, C2H4	200-300	Angle Energy	YES	CNAO 2026
P	C	100-220	Angle Energy	YES	CNAO 2026
C	C, C2H4 PMMA	320-400	Angle Energy	YES	CNAO 2027
He	C, C2H4 PMMA	200-400	Angle Energy	YES	CNAO 2027

➡ New campaigns for the next years

Conclusions

- The FOOT experiment: differential cross sections of interest in Particle Therapy and radio protection in space with an accuracy better than 10%

- Data takings performed at GSI, HIT and CNAO:
  - increasing set-up and performances/calibration
  - improve our detector knowledge: trigger, rate capability, DAQ, on-line monitoring and reconstruction

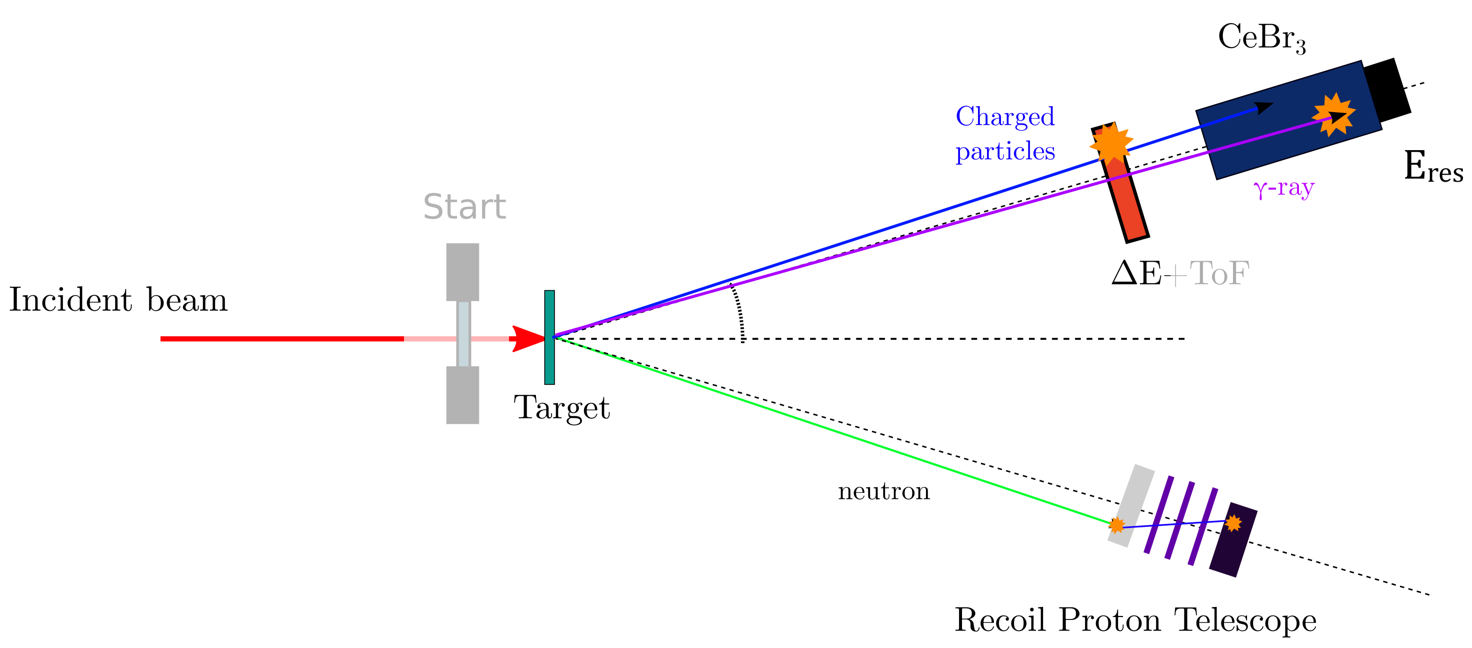
- Physics analysis:
  - Z and/or mass identification for ^{4}He, ^{12}C and ^{16}O beam at different energies impinging on C and C_2H_4
  - First fragmentation cross section measurement of a ^{16}O beam at 400 MeV/u with a partial setup

➡ Huge effort of the collaboration in continous data taking activity, analysis still ongoing …

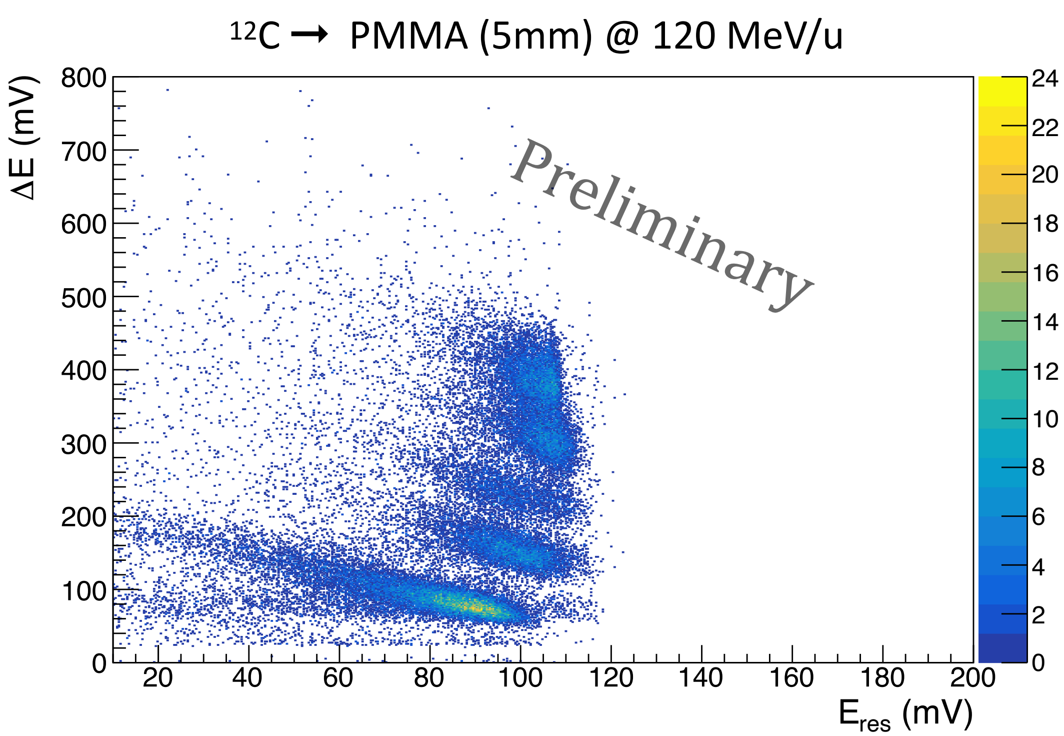
CLINM Project

❑ CLINM (Cross-sections of Light Ions and Neutron Measurements):

- Cross-sections of ^{4}He, ^{12}C, ^{16}O,... ^{56}Fe up to 4 GeV/u
- Correlating the measured data to damages on biomolecules



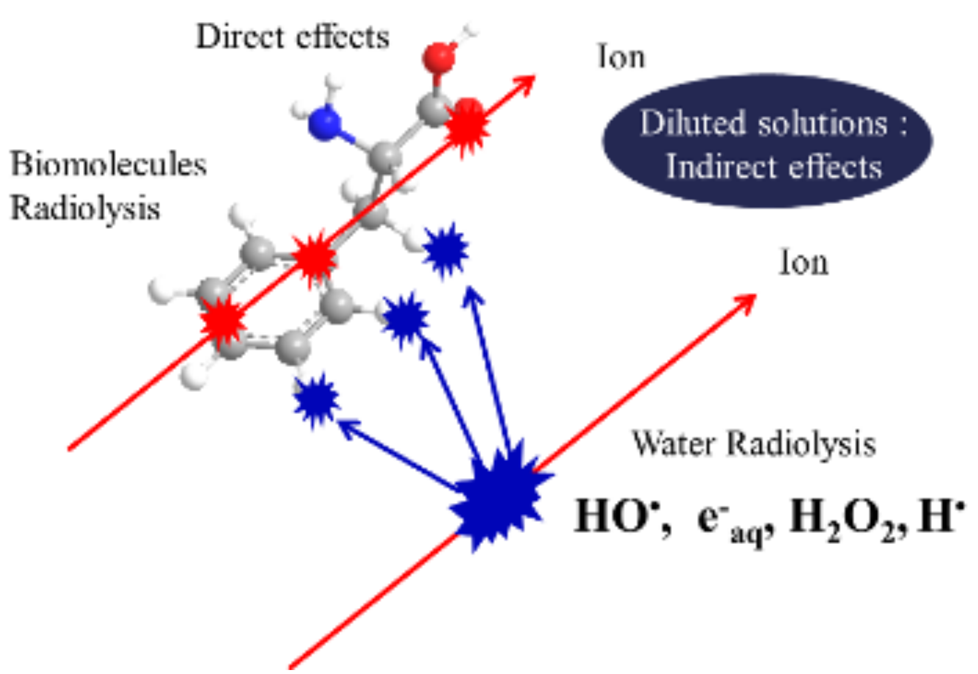
- ΔE-E or ΔE-TOF telescope for charged particles identification
- Neutrons measured by Recoil Proton Telescope (RPT)

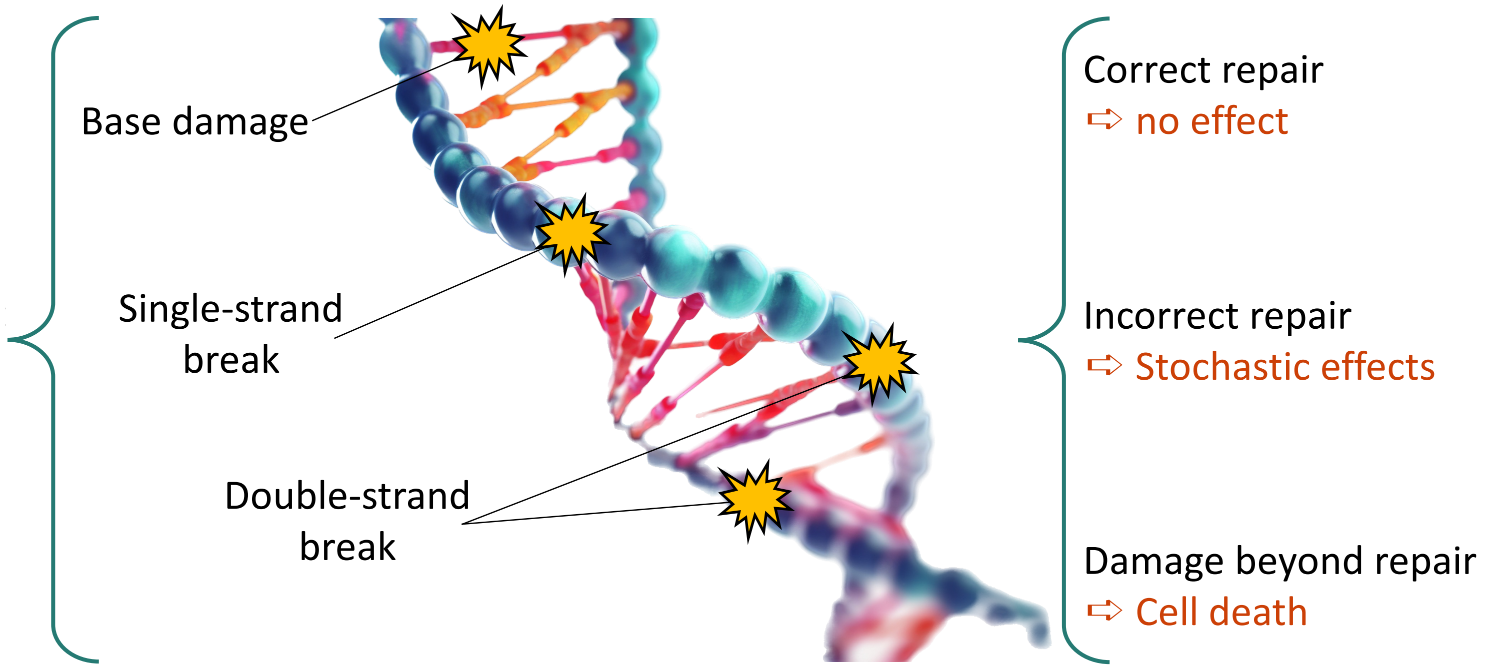


CLINM Project

- Indirect effects
  - responsible for an important part of damages on biomolecules inside the cells (between 30-70%)

Courtesy of L. Gesson

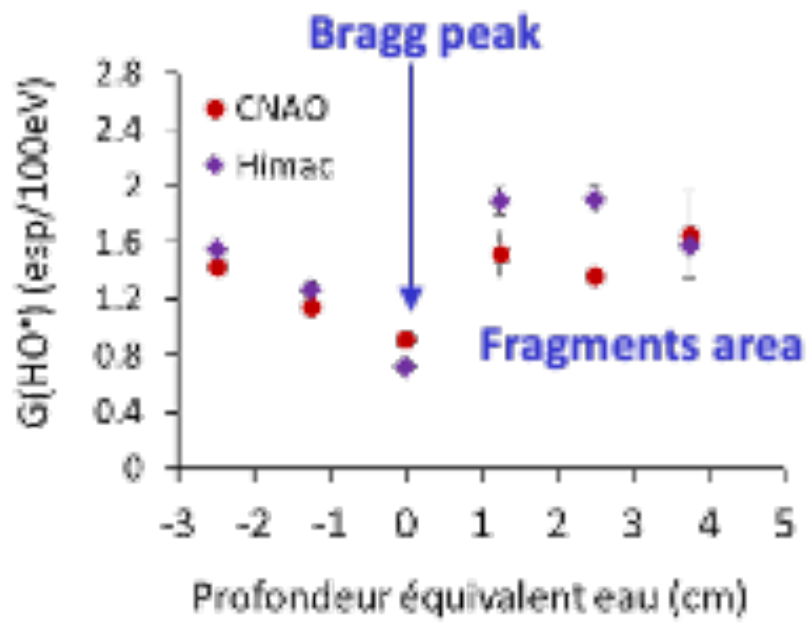


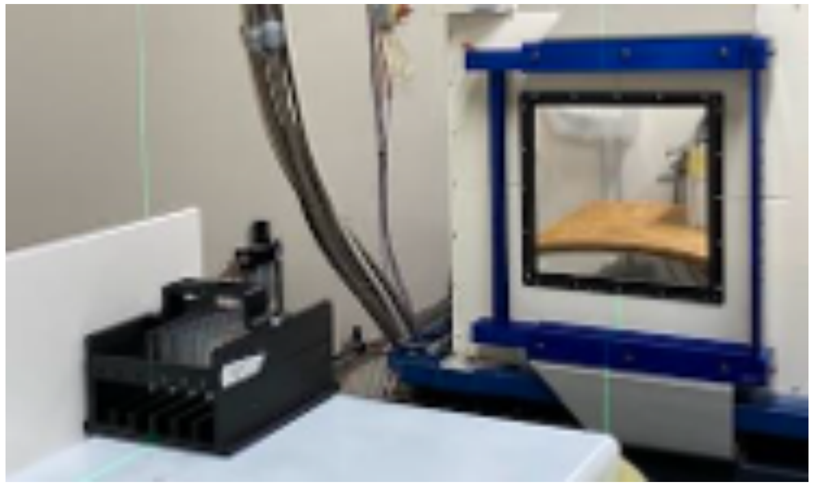


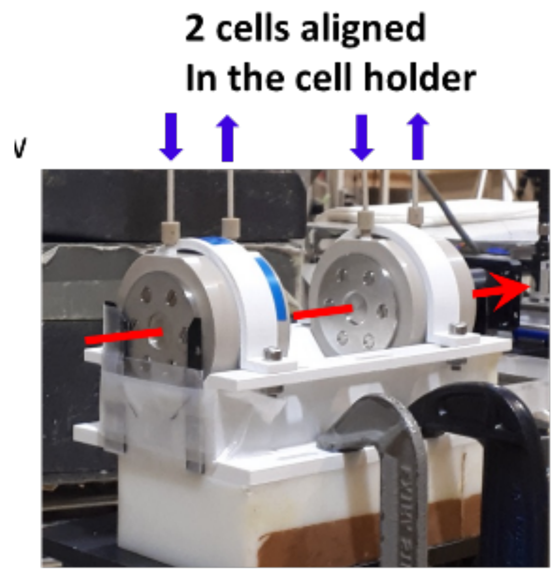
➡ Measure in coincidence fragments and radiolysis

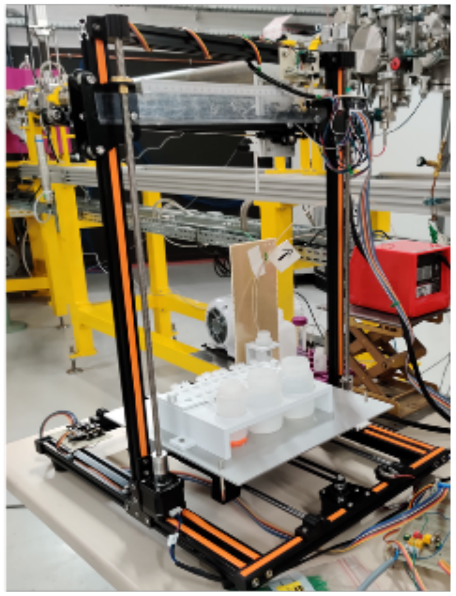
CLINM Project

- Radiolytics
  - responsible for an important part of damages on biomolecules inside the cells (between 30-70%)









➡ Increase of HO* production after the Bragg Peak

➡ First time correlations were observed

Final Conclusions

- Many data to analyse with promising results for FOOT and CLINM
- Ongoing work on both projects
- Start discussion with Geant4 and Geant4-DNA collaboration to introducing model relying of measurement X-sections with introducing AI*

*L. Gesson, G. Henning, J. Collin, M. Vanstalle, *Enhancing nuclear cross-section predictions with deep learning: the DINo algorithm*

The European Physical Journal Plus **140** (7) (2025) **645**

*A. Bigot, *Development of deep learning models for a better prediction power of secondary particles production in Monte Carlo simulations*

Application for ANR funding

Backup