



# Measurements of nuclear fragmentation cross sections and their medical physics & space radio-protection applications

A. Sarti

STRONG-2020 Annual Meeting

# Physics applications?



# Physics applications?

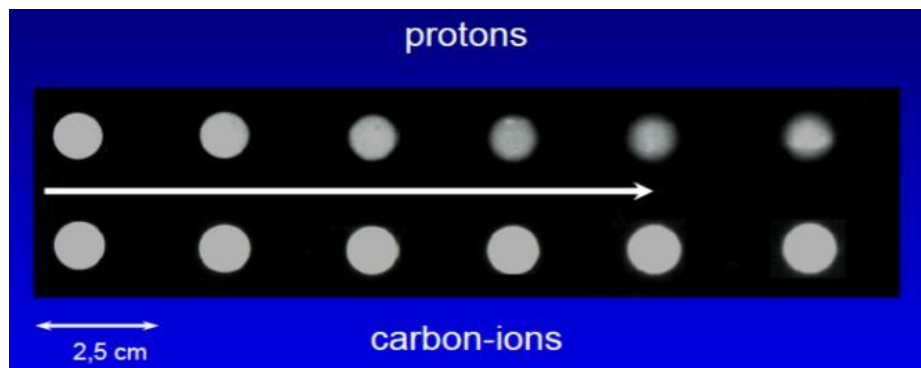
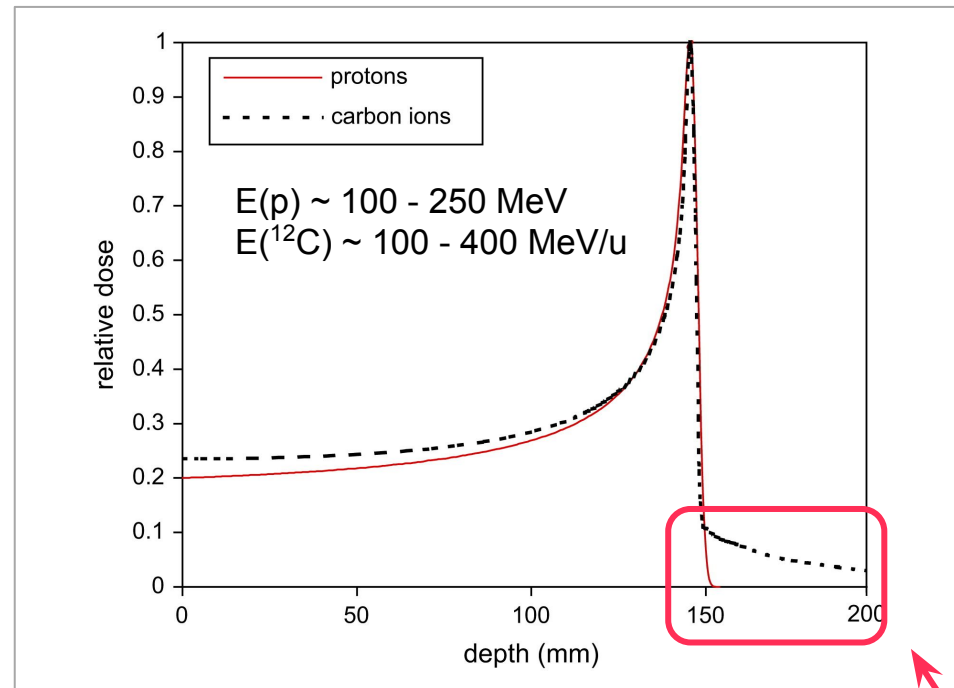
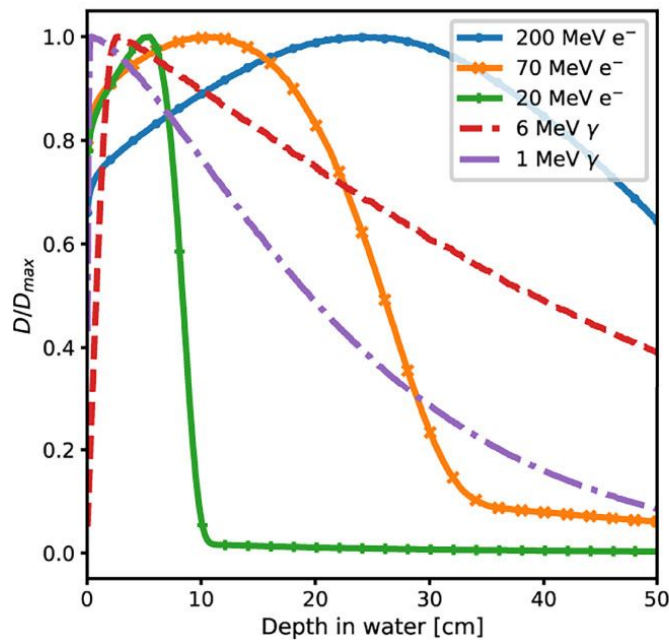
- ➔ There are really many many possible applications of hadronic/nuclear physics... Had not time to make an overview of all the possibilities... **Will focus, in this talk, on two main topics:**
- **Particle Therapy:** use of protons / heavier ions to treat cancer via the ‘External Beam Radio Therapy’ approach .. that is shooting particles to ‘kill’ tumour cells to help/replace the other approaches (chemotherapy, surgical removal)
  - **Space Radio Protection:** astronauts, and their equipment, are constantly exposed to radiation (SPE, GCR).. Planning the proper ‘shielding’ is not a simple technological matter → radiation exposure is one of the limiting factors when discussing missions to Mars or length of stay on the ISS..

Direct link with strong interactions? uhmm... :)

**Monte Carlo sims, data analysis techniques, detectors!**

# Charged nuclei in PT

→ Radiation interacts with matter.. (dear old Bethe-Bloch)



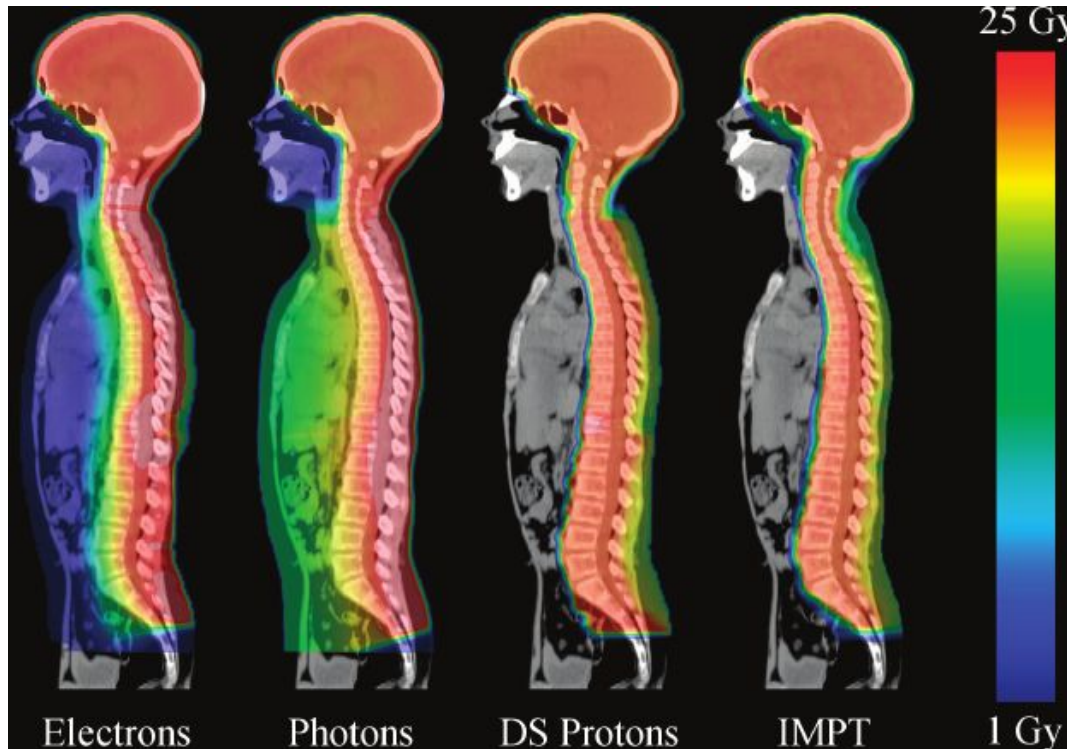
Protons are easier to accelerate...  
but suffer from larger MS interactions..

Instead: only fragmentation occurring  
in proton therapy is the target one..  
while  $^{12}C$  can fragment in flight  
causing **dose tails**..



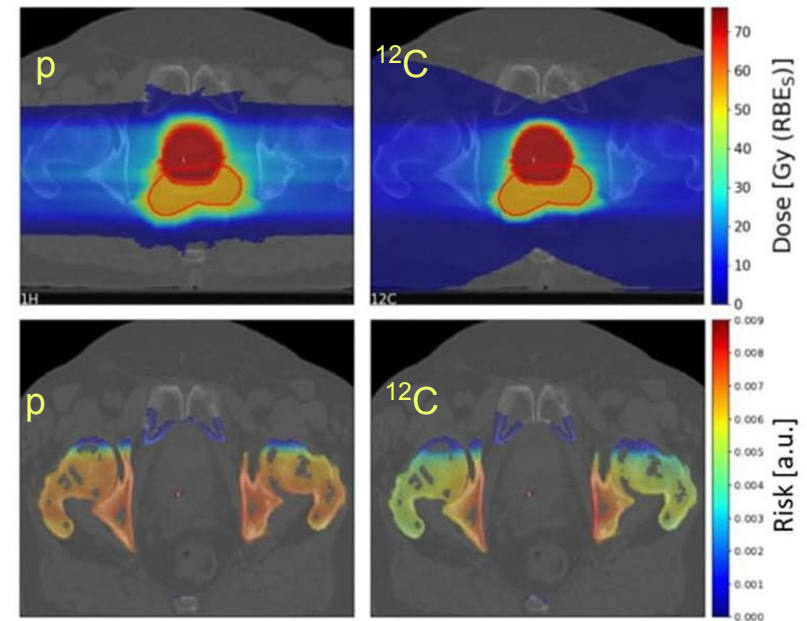
# PT with p & I

→ PT PROs: An image is better than 1000 words...



Stokkevåg, et al (2014). Acta oncologica 53. 1-10. doi 10.3109/0284186X.2014.928420.

RBE-weighted dose distributions (upper panel) and corresponding **bone cancer risk distributions** (lower panel) in the prostate (upper red contour) and seminal vesicles (lower red contour) for a prostate cancer patient after proton (left) and carbon-ion (right) therapy.

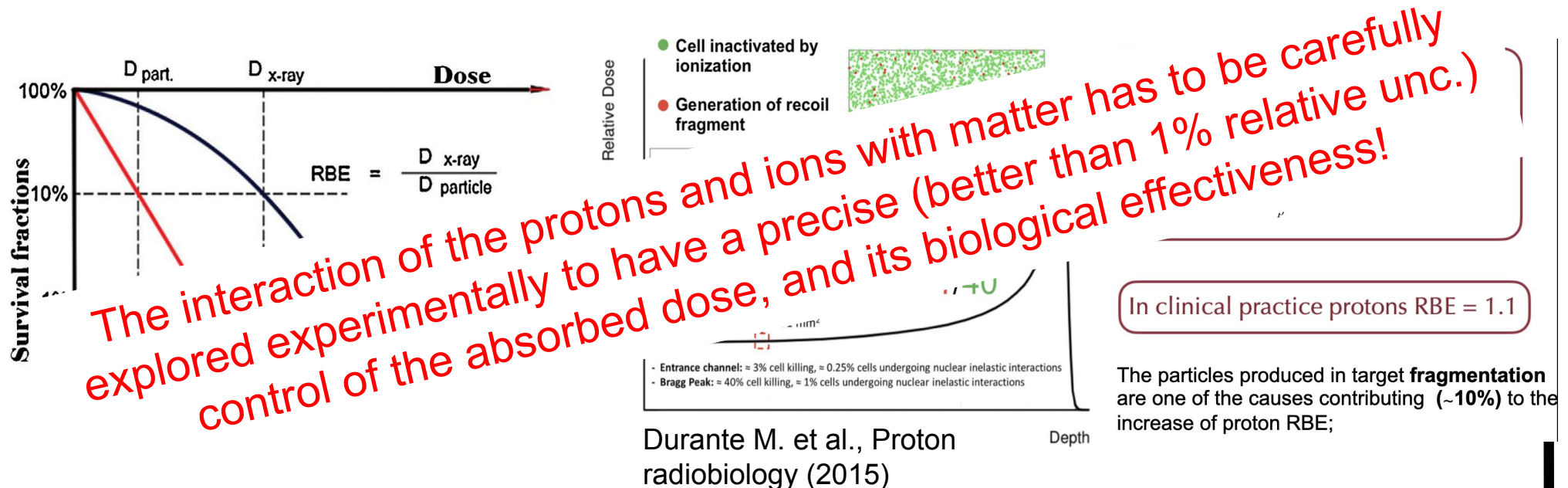


(Courtesy: CC BY 4.0/Med. Phys. 10.1002/mp.15805)

→ PT “Contra”: with great power, comes a great responsibility

# Ions... and 'p-induced' fragm.

- Ions can be either projectiles or targets in PT
- proton therapy: fragmentation contributions comes just from the target fragments
  - heavier ions therapy (mostly  $^{12}\text{C}$ ): fragmentation happens both at proj and tgt level.. But most important contribution is from 'projectile' fragmentation: lighter fragments with longer range wrt initial ion → tail behind BP and possible exposure of Organ at Risk.



# Charged nuclei in SRP

- ➔ Radiation damage is one of largest concerns in Space missions (especially when aiming for the moon or mars..)

*Life* 2014, 4, 491-510; doi:10.3390/life4030491

OPEN ACCESS

*life*

ISSN 2075-1729

www.mdpi.com/journal/life

Review

## Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit

Jeffery C. Chancellor <sup>1,2</sup>, Graham B. I. Scott <sup>1,3</sup> and Jeffrey P. Sutton <sup>1,4,\*</sup>

Prob(%) to develop cancer in life beyond the “natural” level

95% Confidence Interval

Chest X-ray

Diagnostic CT

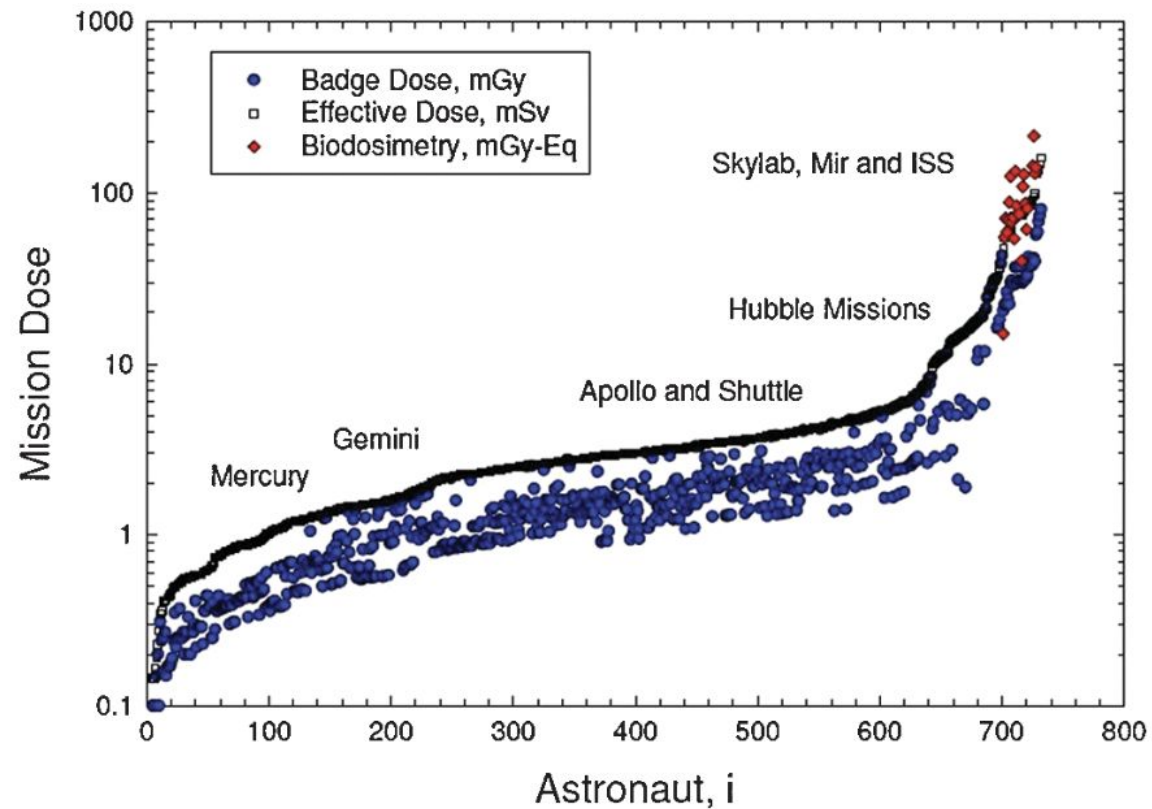
ISS Mission

Lunar Colony

Mars Mission

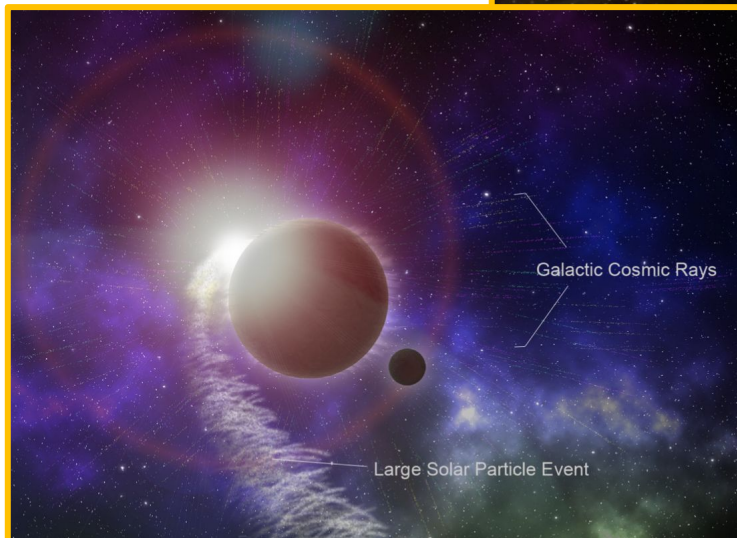
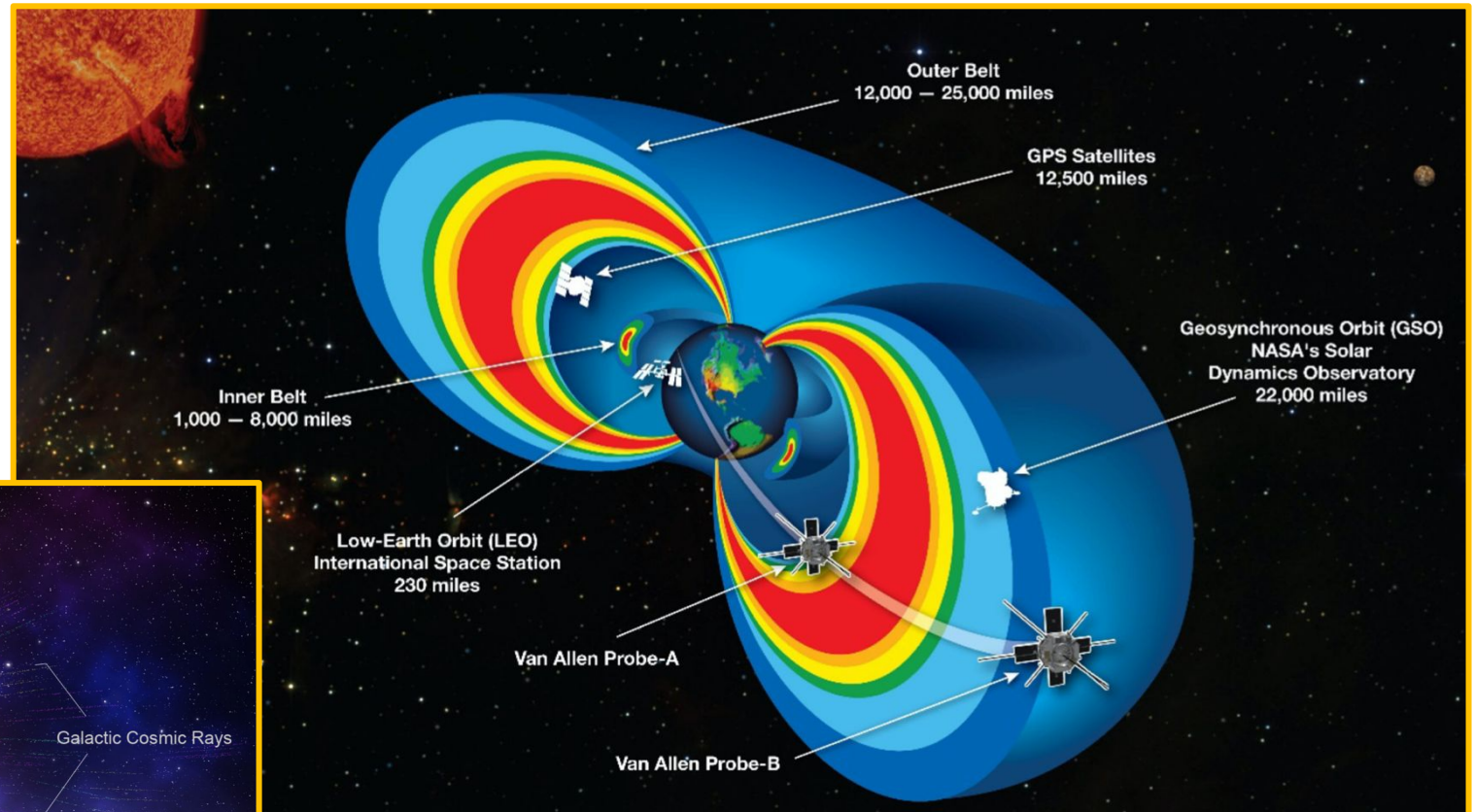
0.001 0.01 0.1 1 10 100

% Risk of Cancer Death





# The SRP environment



- **Galactic Cosmic Rays GCR (all ions)**
- **Solar Particle Events SPE (mainly protons)**
- Trapped particles (protons and electrons)
- Albedo radiation (electrons, protons, neutrons)

# SPEs ...

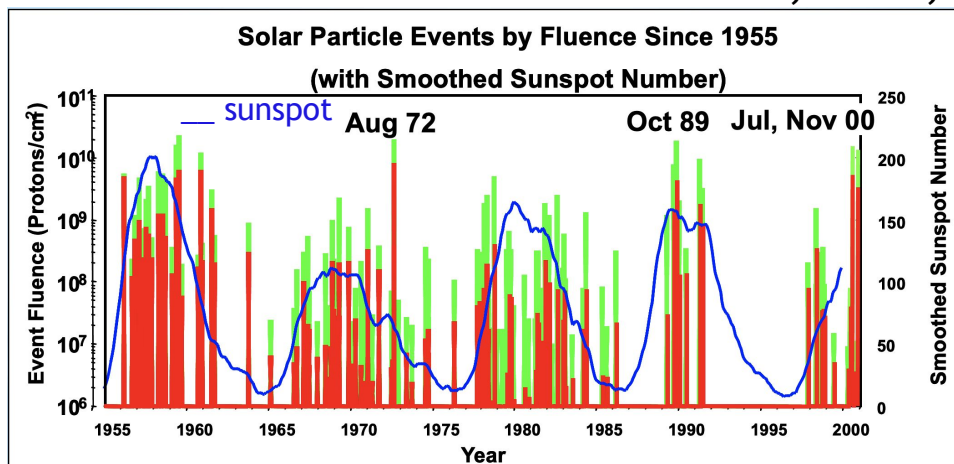
## Solar Particle Events : sudden emission by the Sun

**Flux:** up to  $\sim 10^{10}$  particles/cm<sup>2</sup> in hrs,  
depending on Sun distance

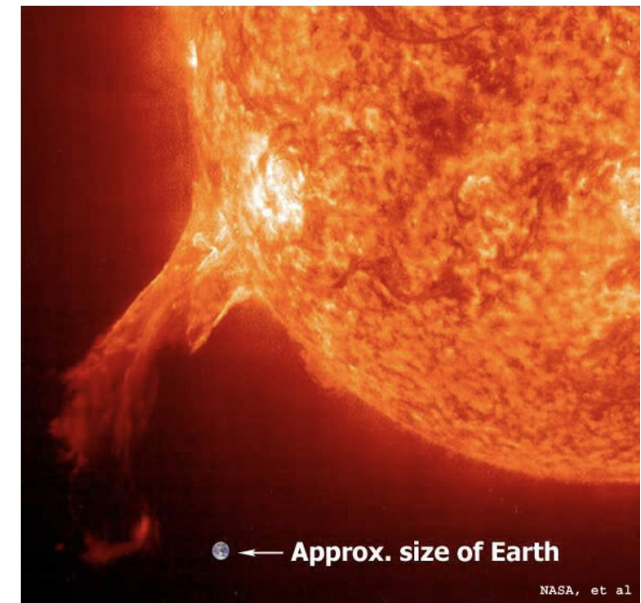
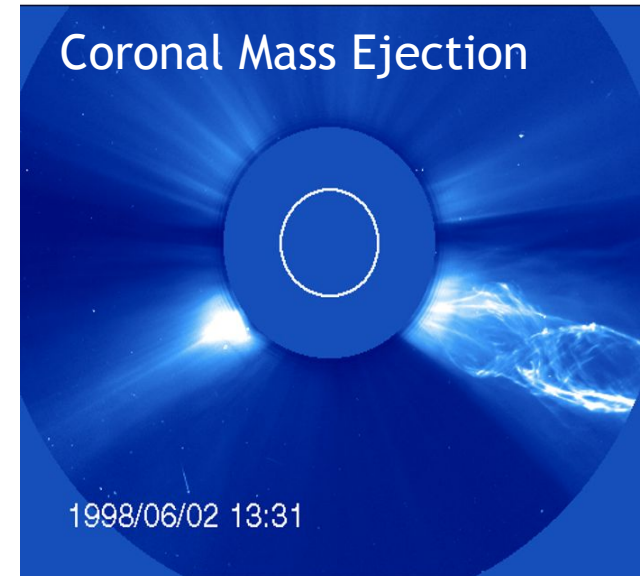
**Dose:** order of Sv, strongly dependent on  
shielding and organ

**Frequency:** almost unpredictable, function  
of solar cycle

R Turner, ANSER, Inc.



## Coronal Mass Ejection



# .. and GCR spectra

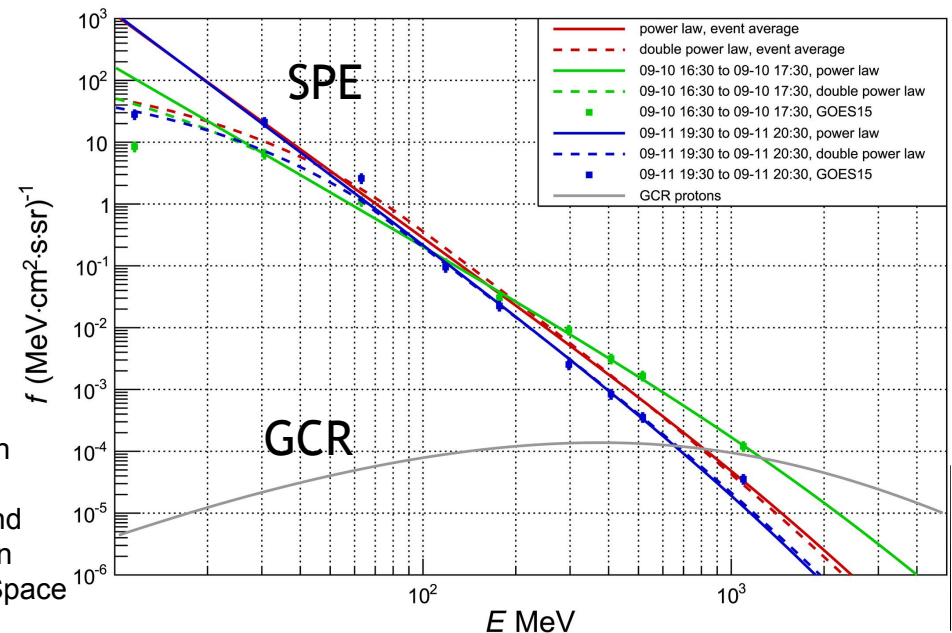
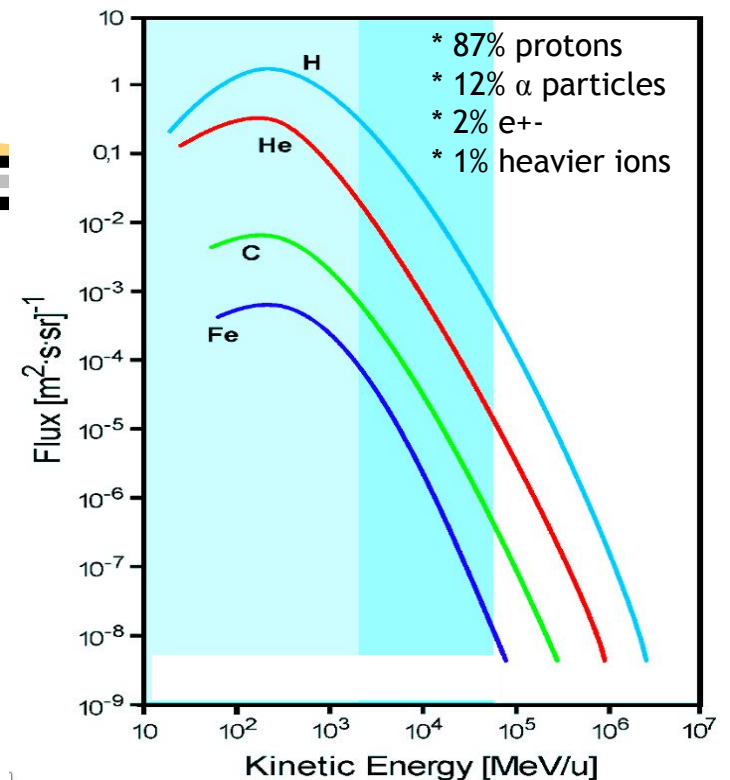
Galactic Cosmic Ray: continuous isotropic flux

**Spectrum:** 90% protons, 10% heavier ions ( $\sim^4\text{He}$ ), energy peaked at 1 GeV/nucleon

**Flux:** constant in time, isotropic, few particles/cm<sup>2</sup>

**Dose:** order of  $\sim 1$  mSv/d in outer space (1 year dose on Earth)

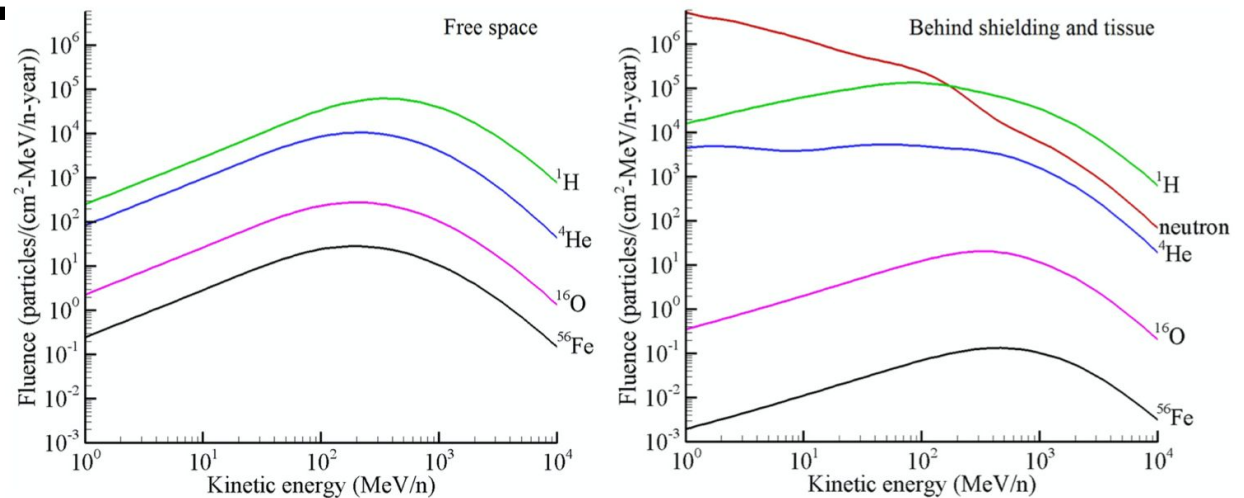
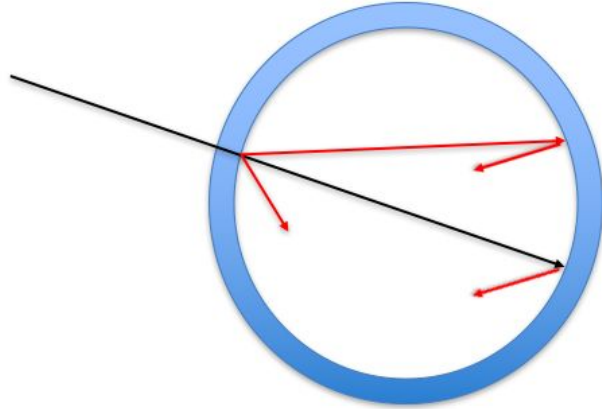
Penetrating particles, need heavy shielding to be stopped



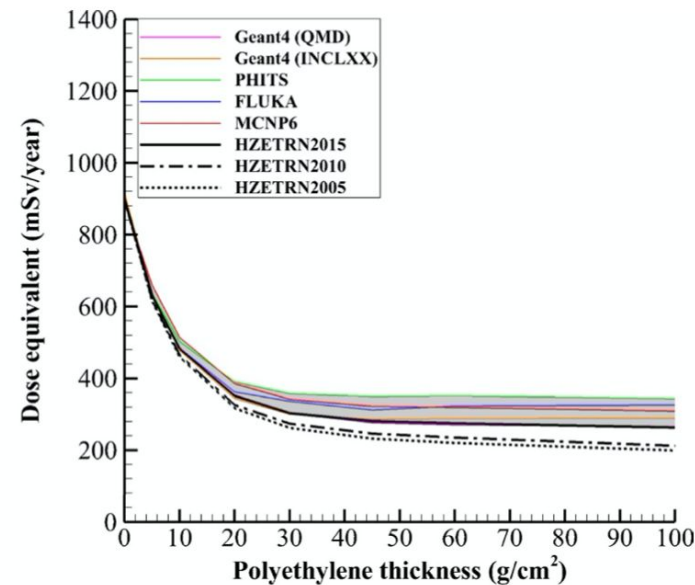
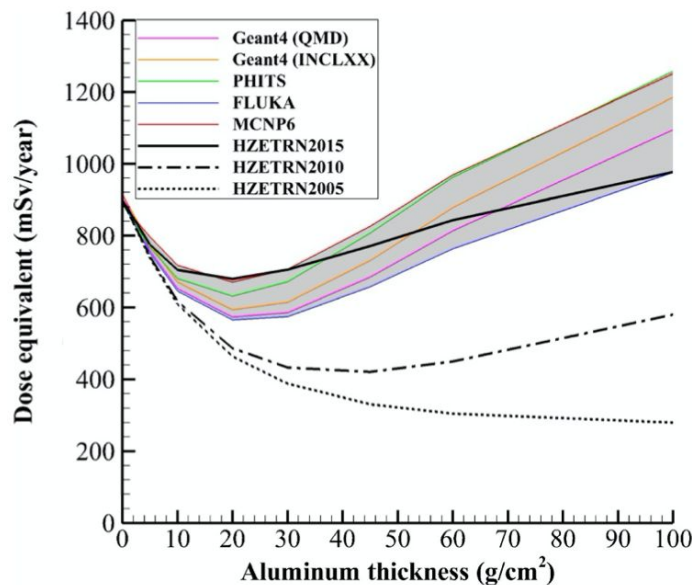
The Solar Particle Event on 10–13 September 2017: Spectral Reconstruction and Calculation of the Radiation Exposure in Aviation and Space



# Goal: shielding design

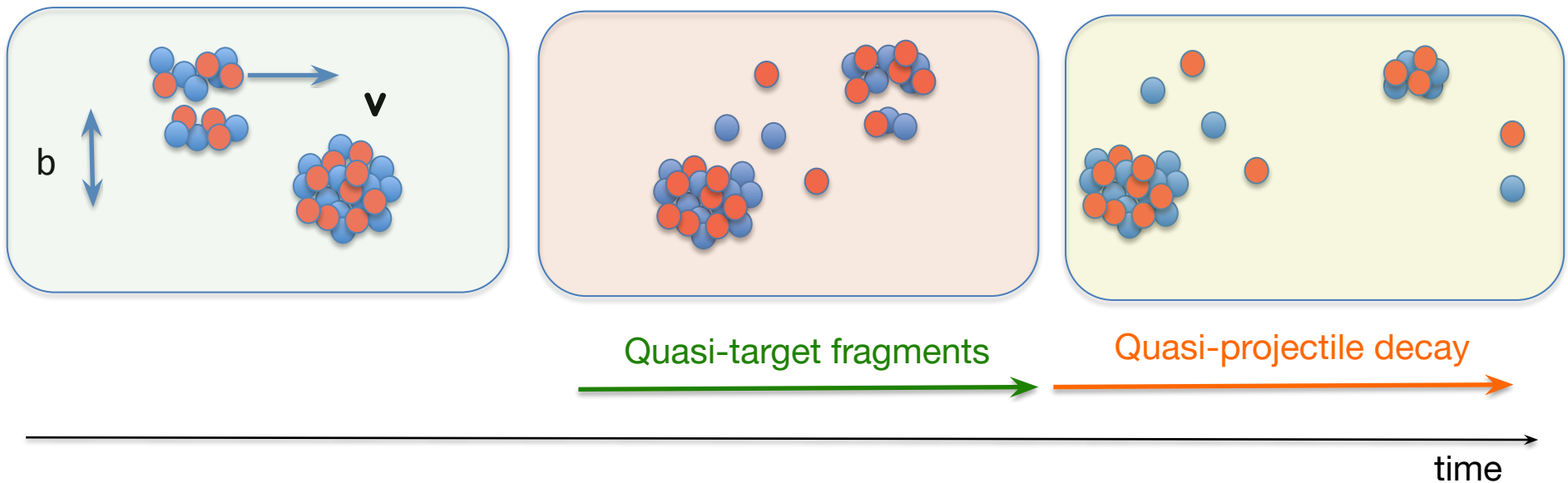


Transport codes indicate that the strategy of “the more the better” does not always work in space.



# The 'underlying' physics..

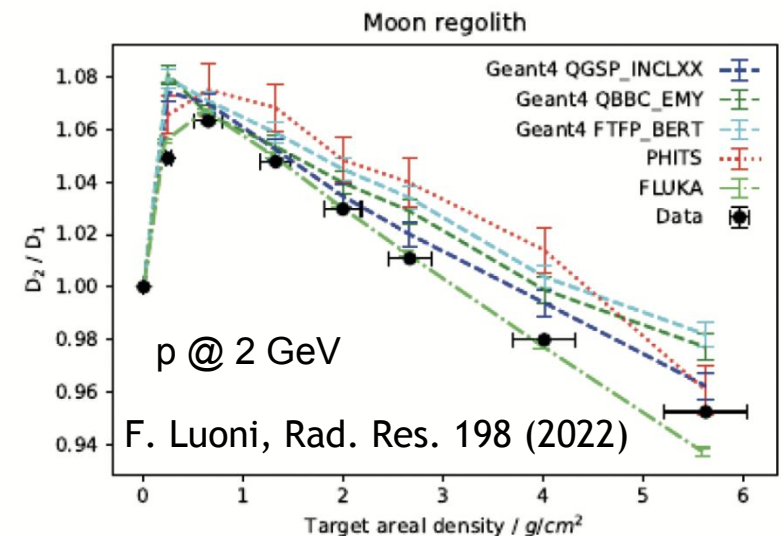
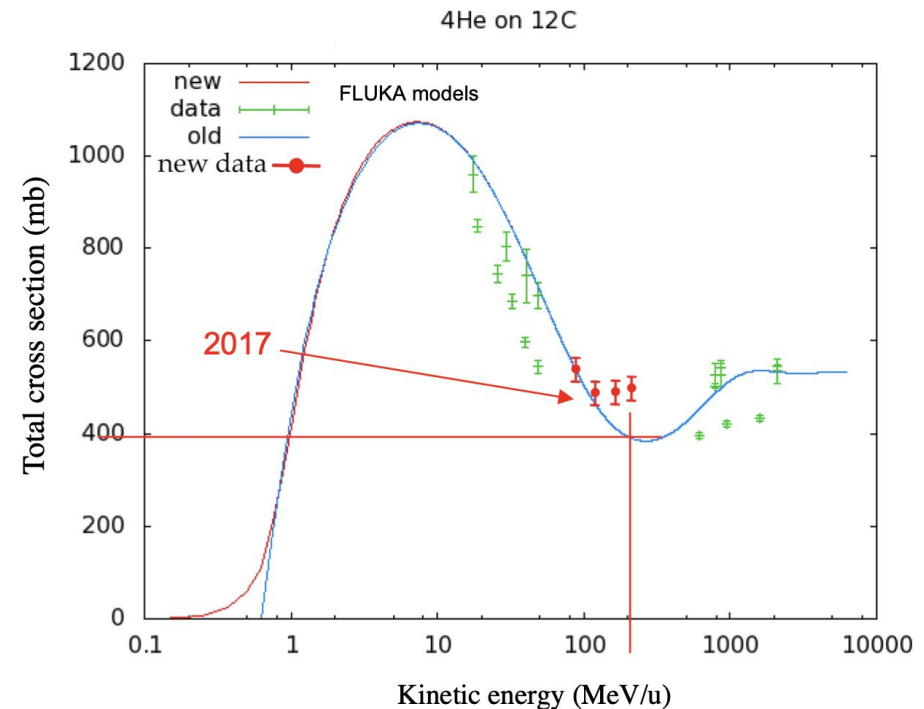
## The abrasion - ablation paradigm



- Fragments from quasi-projectile have  $V_{\text{frag}} \sim V_{\text{beam}}$  and narrow emission angle. Longer range than beam
- The other fragments have wider angular distribution but lower energy. Usually light particles (p,d,He)
- The dose beyond the distal part comes from the quasi projectile contribution. Wide angular halo from the rest of the process

# What do we need?

- The control on the absorbed dose needs to reach the few % level.. Current MC models have not yet reached such precision → **lack of input experimental data!**
- Literature provides mostly integrated CS. Instead, **double differential cross sections are needed**.. on several different targets:
  - PT studies: main constituents of human body (H, O, C.. and then N, Ca)
  - SRP: more interesting/exotic.. e.g. moon regolith!



# Exp overview... (direct DDCS)

- The double differential cross sections ( $E_{kin}$ ,  $\vartheta$ ) are missing in the energy range of interest for applications!
- Models are available, but suffer from significant uncertainties: need dedicated exp. campaign to improve MC simulation reliability @ level of clinical applications

Total CC cross sections of fragm  
against H targets [4]

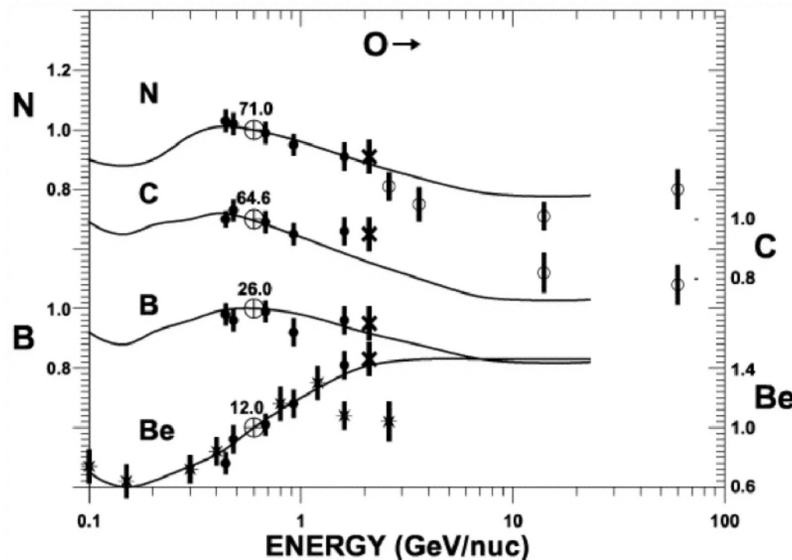


Figure 8 – Double differential cross sections available from literature for the production of medium-light fragments ( $Z_F = 3 - 9$ ). The data are shown as function of projectile and target charge  $Z$  and divided into two projectile energy ranges (below 290 MeV/u and between 290 MeV/u and 3 GeV/u).

<https://crosssection-db.herokuapp.com/>

Projectile atomic number	Target chemical formula	Projectile kinetic energy (MeV/u)	Cross-section type	First author of the publication	Year of publication
All	All	All	All	All	All
8	C	288	cc Integrated in Z	Yamaguchi [1]	2011
8	H2O (Water)	300	cc no cross-section	Schall [3]	1996
8	H	387	cc only H target	Webber [4]	1998
8	H	290	cc	Zeitlin	2011
8	C	290	cc	Zeitlin	2011
8	H	400	cc	Zeitlin	2011
8	C	400	cc	Zeitlin	2011

[1] <https://doi.org/10.1103/PhysRevLett.107.032502>

[2] <https://doi.org/10.1103/PhysRevC.83.034909>

[3] [https://doi.org/10.1016/0168-583X\(96\)00325-4](https://doi.org/10.1016/0168-583X(96)00325-4)

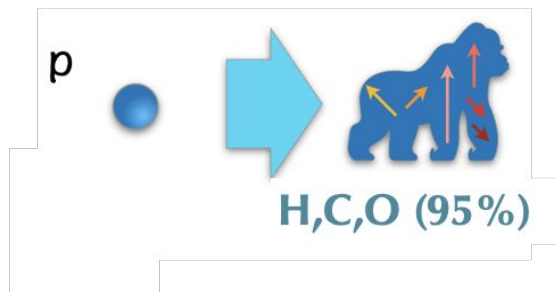
[4] <https://iopscience.iop.org/article/10.1086/344051/>

[3] Charge-changing nuclear reactions of relativistic light-ion beams ( $5 \leq Z \leq 10$ ) passing through thick absorbers.

# p induced fragmentation..

- ➔ much tougher! Fragments produced @ E of interest for PT have energies/ranges of  $\sim \mu\text{m}$

## Direct kinematic

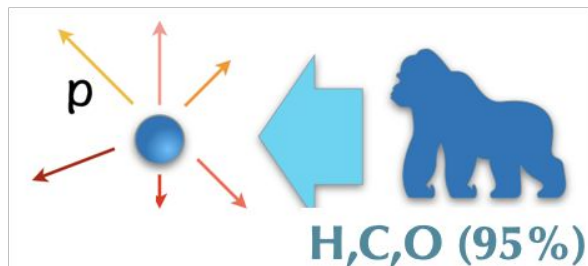


$$p(180\text{MeV}) + X(\text{water}) \rightarrow p' + X'_i$$

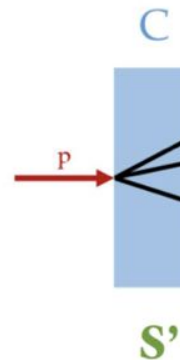
Fragment	E [MeV]	LET (keV/ $\mu\text{m}$ )	Range ( $\mu\text{m}$ )
$^{15}\text{O}$	1.0	983	2.3
$^{15}\text{N}$	1.0	925	2.5
$^{14}\text{N}$	2.0	1137	3.6
$^{13}\text{C}$	3.0	951	5.4
$^{12}\text{C}$	3.8	912	6.2
$^{11}\text{C}$	4.6	878	7.0

Target fragments have a very **low energy** and **short range**. Their experimental detection is extremely difficult.

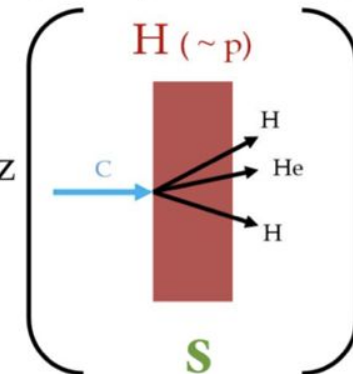
## Inverse kinematic



Proton beam on patient-target  
(Patient frame of reference)



Patient-target on Proton beam  
(Laboratory frame of reference)



= Lorentz  
Boost

➔ In this case the fragments have a longer range and a mean kinetic energy comparable to the projectile one.

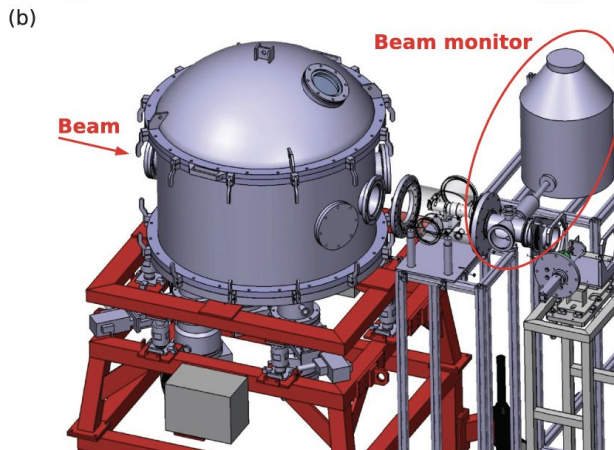
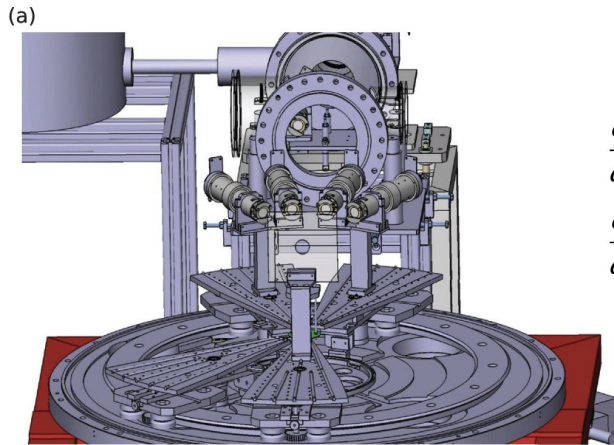


# The challenge(s)

→ Fragments separation... and cross section subtraction..

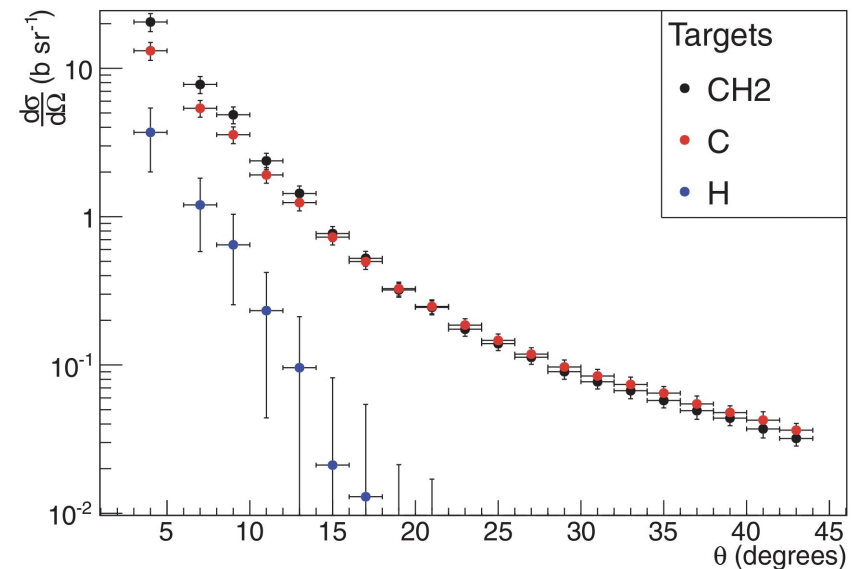
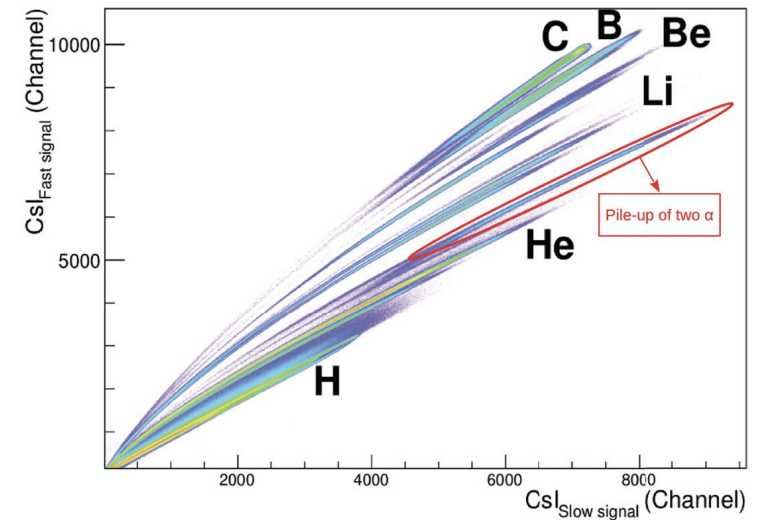
PHYSICAL REVIEW C 88, 024606 (2013)

Double-differential fragmentation cross-section measurements of 95 MeV/nucleon  $^{12}\text{C}$  beams on thin targets for hadron therapy



$$\frac{d\sigma}{d\Omega}(\text{H}) = \frac{1}{2} \times \left( \frac{d\sigma}{d\Omega}(\text{CH}_2) - \frac{d\sigma}{d\Omega}(\text{C}) \right),$$

$$\frac{d\sigma}{d\Omega}(\text{O}) = \frac{1}{3} \times \left( \frac{d\sigma}{d\Omega}(\text{Al}_2\text{O}_3) - 2 \times \frac{d\sigma}{d\Omega}(\text{Al}) \right).$$





# The experimental quests

[<https://tel.archives-ouvertes.fr/LPCC-AMI/hal-02959536v1>]

- ➔ **FRACAS @ ARCADE** (Advanced Resource Center for HADrontherapy in Europe, Caen, France)
  - DDCS btw 100 and 400 MeV/u for H, N, O, C, Ca
- ➔ **The FragmentatiOn Of Target (FOOT) experiment**, focuses on nuclear interaction effects on Particle Therapy & Radio Protection in Space



Nagoya University (Japan), GSI (Germany)

Aachen University (Germany), IPHC Strasbourg (France), CNAO (Italy)

10 Italian University/INFN sections

most of the funding from INFN (2017-2022)

80 researchers, 60% permanent, 40 FTE

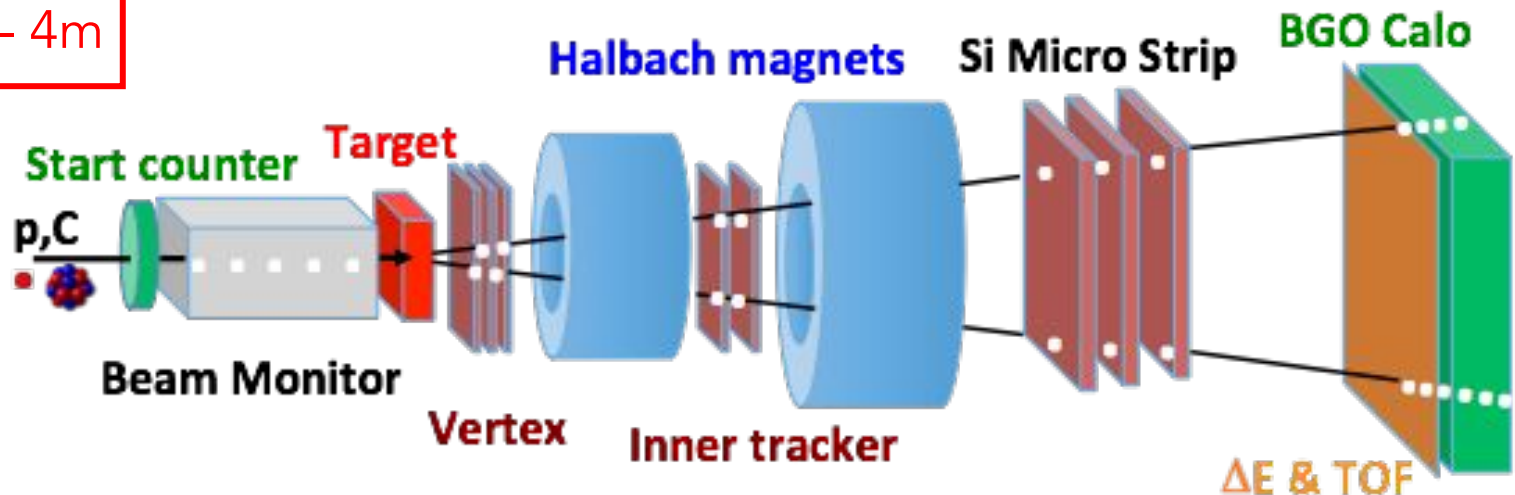
Double detector : emulsion setup for light fragments and electronic setup for  $Z > 2$  fragments

First run at GSI April 2019. Experiment lifetime >2024

# The FOOT experiment

Size ~ 2m – 4m

Forward exp.  
with small  
angular  
aperture!  
Cover 'only' up  
to  $5.7^\circ$



Sub-detector	Main characteristics
Start counter	plastic scintillator 250 $\mu\text{m}$
Beam monitor	drift chamber (12 layers of wires)
Target	$C+C_2H_4$ (2 mm)
Vertex	4 layers silicon pixel (20x20 $\mu\text{m}$ )
Magnet	2 permanent dipoles ( $\sim 1$ T)
Inner tracker	2 layers silicon pixel (20x20 $\mu\text{m}$ )
Outer tracker	3 layers silicon strip (125 $\mu\text{m}$ pitch)
Scintillator	2 layers of 20 bars (2x40x0.3 $\mu\text{m}$ )
Calorimeter	360 BGO crystals (2x2x14 $\mu\text{m}$ )

## Target performances

- $\Delta p/p < 2.5\%$
- $\Delta_{\text{TOF}} < 70\text{ps}$
- $\Delta E_{\text{kin}}/E_{\text{kin}} < 2\%$
- $\Delta(dE)/dE \sim 3\%$

For now... not considering neutrons at all!!  
[there are ] plans for FOOT upgrades, but  
neutrons remain uncovered so far!

# FOOT physics plan

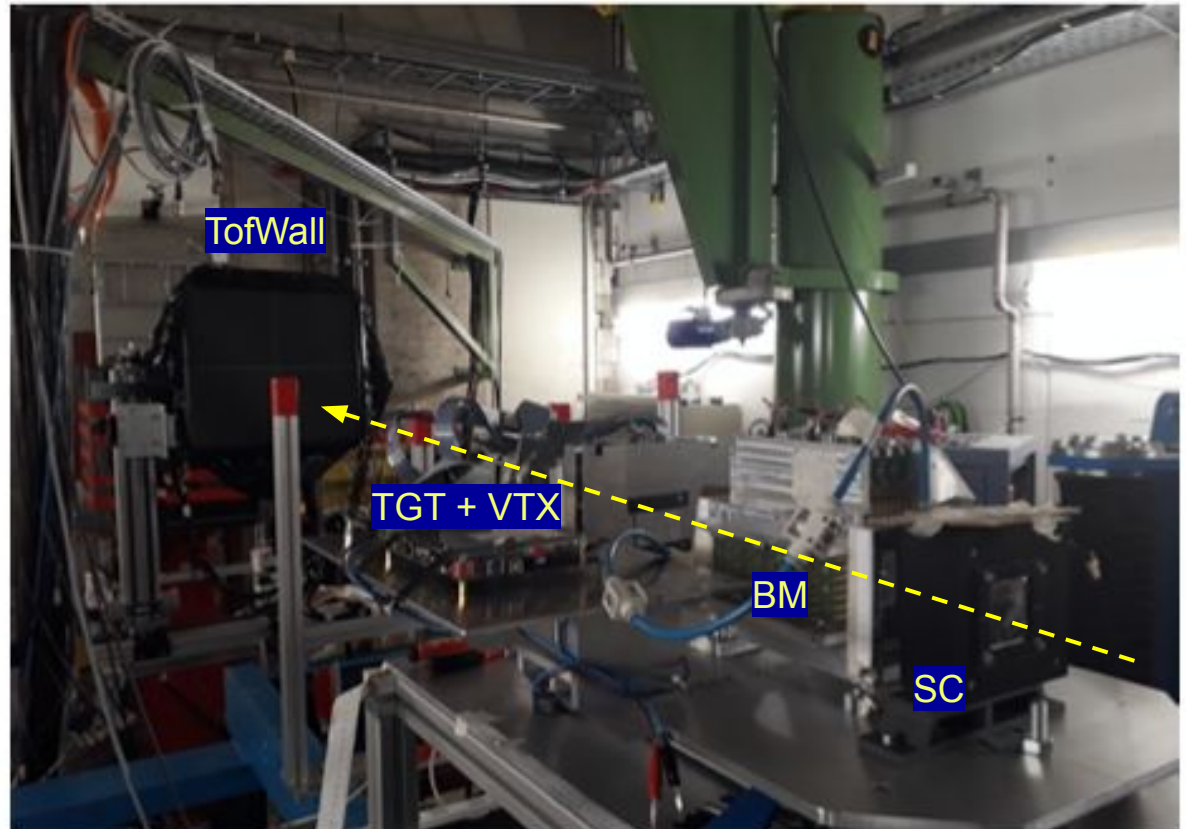
ALL data from the three targets C, C<sub>2</sub>H<sub>4</sub> and PMMA are needed to obtain the elemental cross sections on C, O and H

FOOT is designed to be movable. Coordination among different facilities could speed up the accomplishment of the program

Phys	Beam	Target	Energy (MeV/u)	Facility
Target Frag. PT	<sup>12</sup> C	C, C <sub>2</sub> H <sub>4</sub>	100-200	GSI, HIT, CNAO
Target Frag. PT	<sup>16</sup> O	C, C <sub>2</sub> H <sub>4</sub>	100-200	GSI, HIT
Beam Frag. PT	<sup>12</sup> C	C, C <sub>2</sub> H <sub>4</sub> , PMMA	200-350	GSI, HIT, CNAO
Beam Frag. PT	<sup>16</sup> O	C, C <sub>2</sub> H <sub>4</sub> , PMMA	200-400	GSI, HIT
Beam Frag. PT	<sup>4</sup> He	C, C <sub>2</sub> H <sub>4</sub> , PMMA	150-250	GSI, HIT
Rad. Prot.space	<sup>4</sup> He	C, C <sub>2</sub> H <sub>4</sub> , PMMA	500-1000	GSI
Rad. Prot.space	<sup>12</sup> C	C, C <sub>2</sub> H <sub>4</sub> , PMMA	500-1000	GSI
Rad. Prot.space	<sup>16</sup> O	C, C <sub>2</sub> H <sub>4</sub> , PMMA	500-1000	GSI

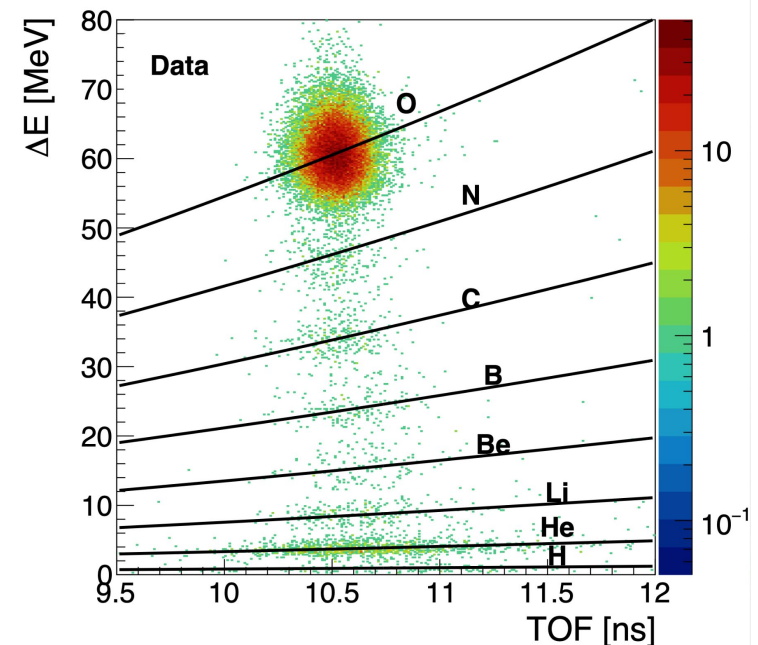
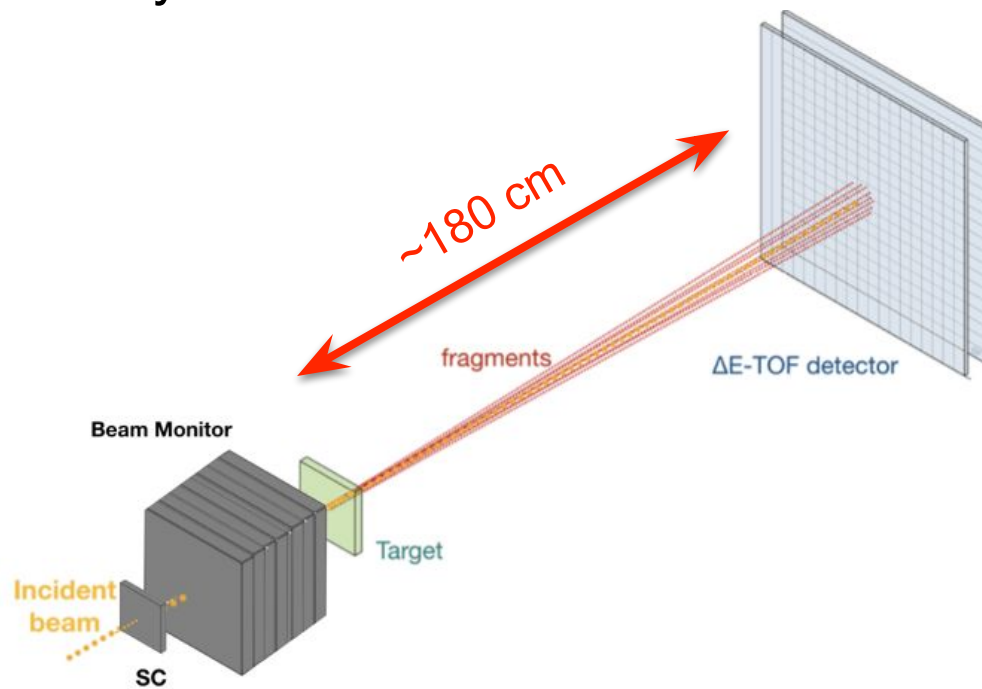
# FOOT experimental status

- Experiment under construction since 2019.. Current issue is the assembly of the permanent magnets → going for integrated cross sections
- First data taking @ GSI with SC, BM, target & TofWall
  - already able to measure some charge changing cross section for  $^{16}\text{O}$  of 400 MeV/u on graphite!



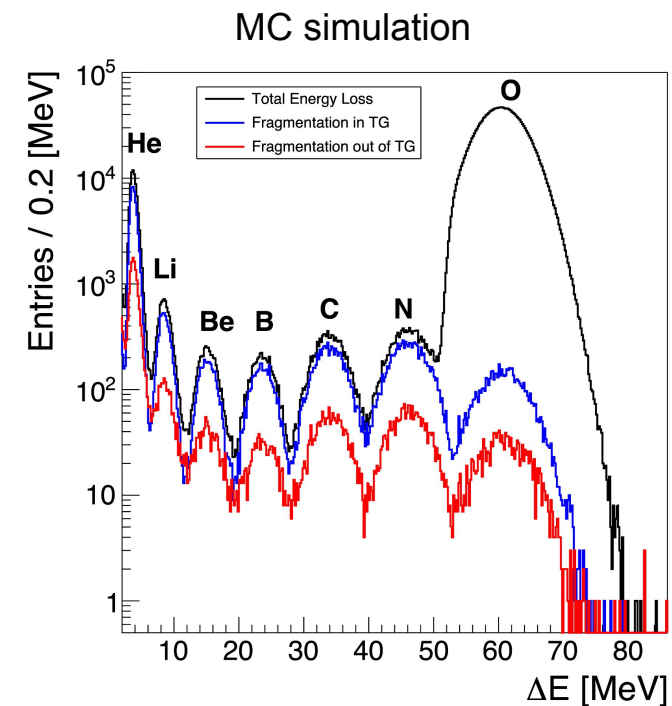
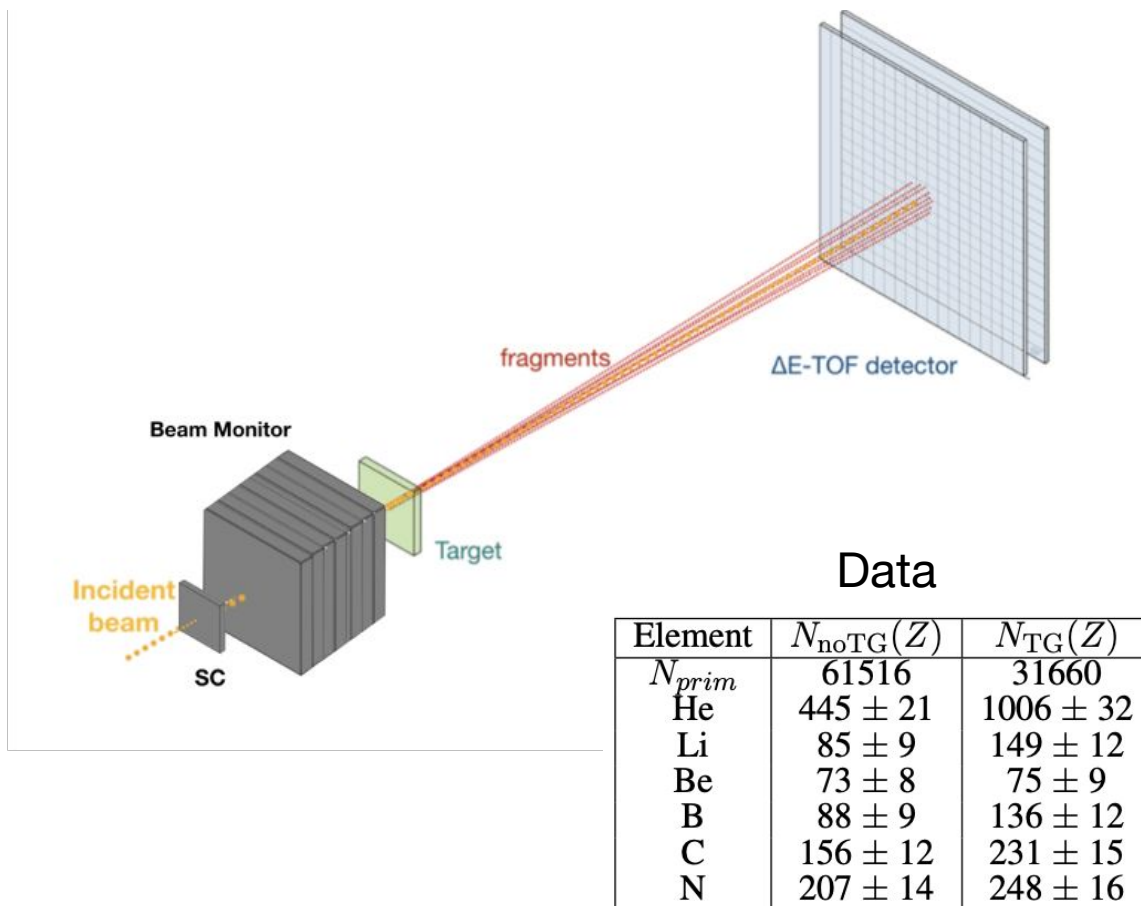
# The first runs.. $^{16}\text{O}$ , 400 MeV/u @ GSI

- ➔ Without magnets / trackers → Z id is performed by means of dE/dx vs time of flight measurements
  - Measurements precision limited by statistics: max rate of 1kHz due to 'slow' readout of TW + small target thickness to avoid re-fragmentation of ions inside the tgt... → small fragmentation yield



# The background subtraction

- The experiment is carried out 'in air' and care has to be taken in subtracting the 'out of target' fragmentation → calibrated on data, removing the target





# $\sigma(Z)$ measurements

$$\sigma(Z) = \int_{E_{\min}}^{E_{\max}} \int_0^{\Delta\theta} \left( \frac{\partial^2 \sigma}{\partial \theta \partial E_{\text{kin}}} \right) d\theta dE_{\text{kin}} = \frac{N_{\text{frag}}(Z)}{N_{\text{prim}} \cdot N_{\text{TG}} \cdot \varepsilon(Z)}$$

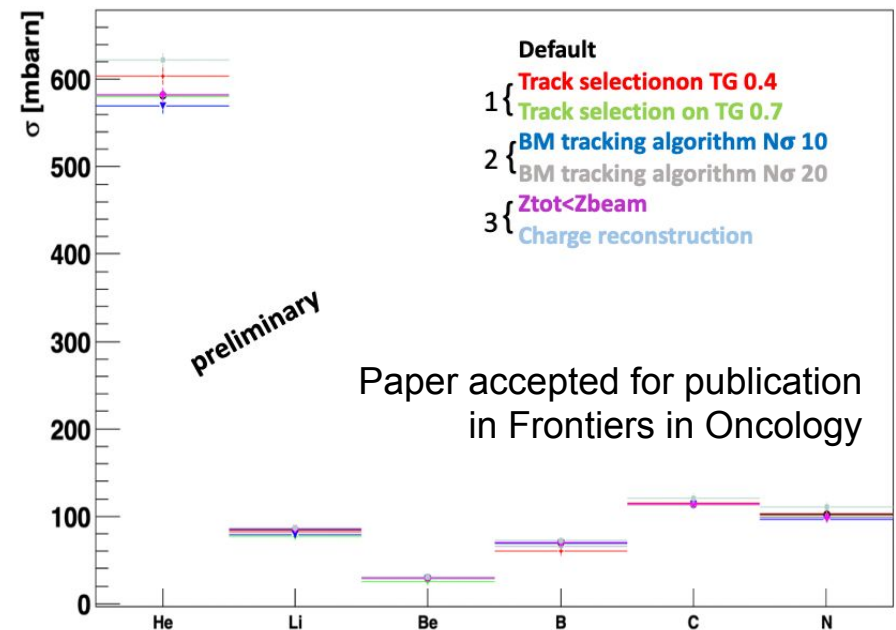


$$N_{\text{TG}} = \frac{\rho \cdot dx \cdot N_A}{A} \quad \begin{cases} \rho = 1.83 \text{ g/cm}^3 \\ dx = 0.5 \text{ cm} \\ A = 12.0107 \end{cases}$$

$\varepsilon(Z)$  accounts for geometrical acceptance and reconstruction efficiencies and is evaluated by means of a FLUKA MC simulation

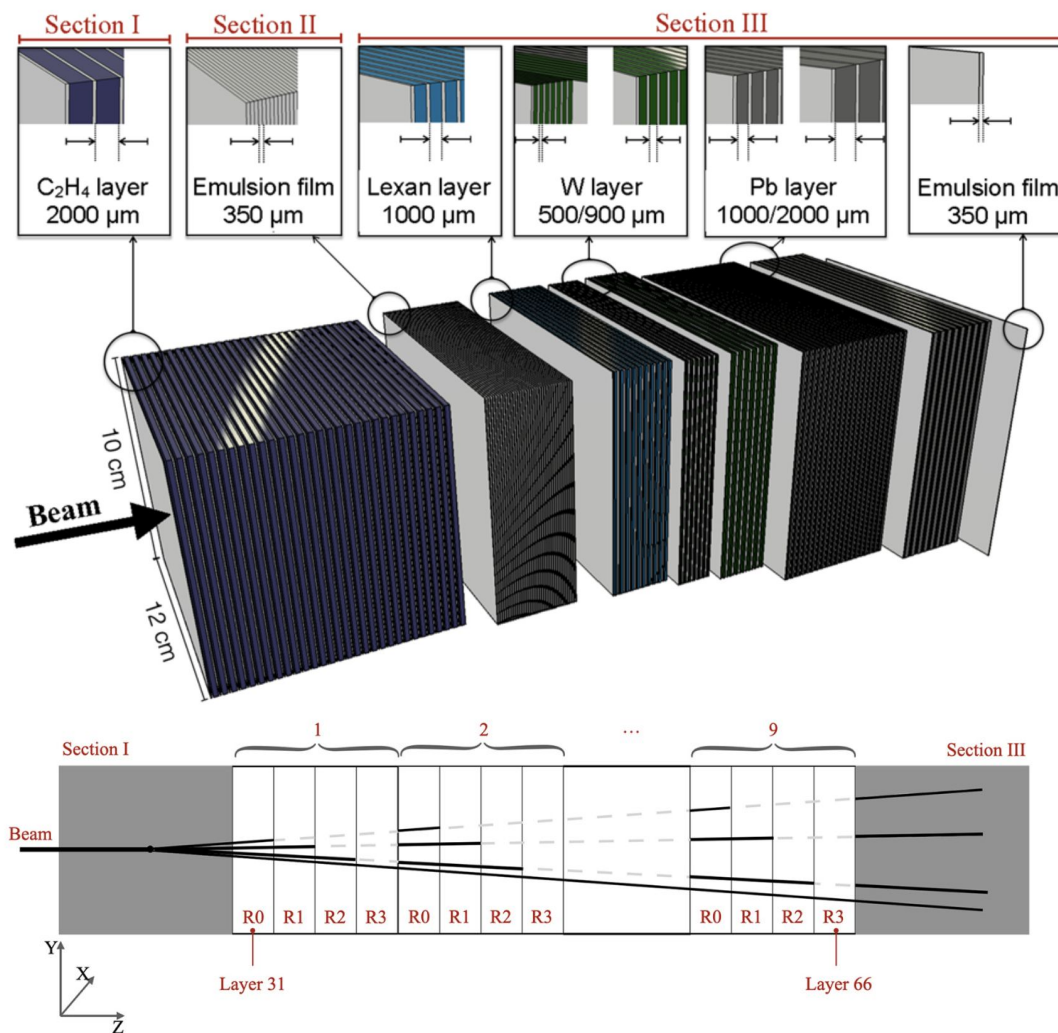
Nice agreement btw data and MC (except for B)

Element	$\sigma_{\text{frag}} \pm \Delta_{\text{stat}} \pm \Delta_{\text{sys}} [\text{mbarn}]$	$\Delta_{\text{stat}} / \sigma_{\text{frag}}$	$\Delta_{\text{sys}} / \sigma_{\text{frag}}$	$\sigma_{\text{MC}} [\text{mbarn}]$
He	$625 \pm 22 \pm 21$	3.6%	3.6%	621
Li	$85 \pm 10 \pm 5$	11.9%	5.6%	67
Be	$31 \pm 10 \pm 3$	31.8%	8.8%	33
B	$70 \pm 10 \pm 5$	14.9%	7.3%	38
C	$113 \pm 12 \pm 3$	10.9%	2.7%	81
N	$101 \pm 14 \pm 5$	13.7%	4.8%	105



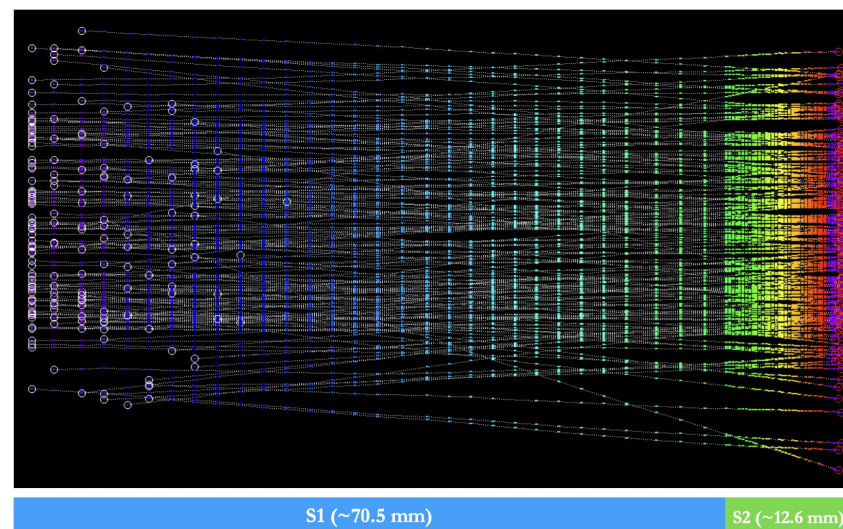
# ECC a 'full' compact detector!

→ To recover angular acceptance... Emulsion 'cloud' chambers!



Section 1: interaction + vertexing  
Section 2: charge identification!  
Section 3: momentum measurements (range)

Matching tracks btw S1 & S2

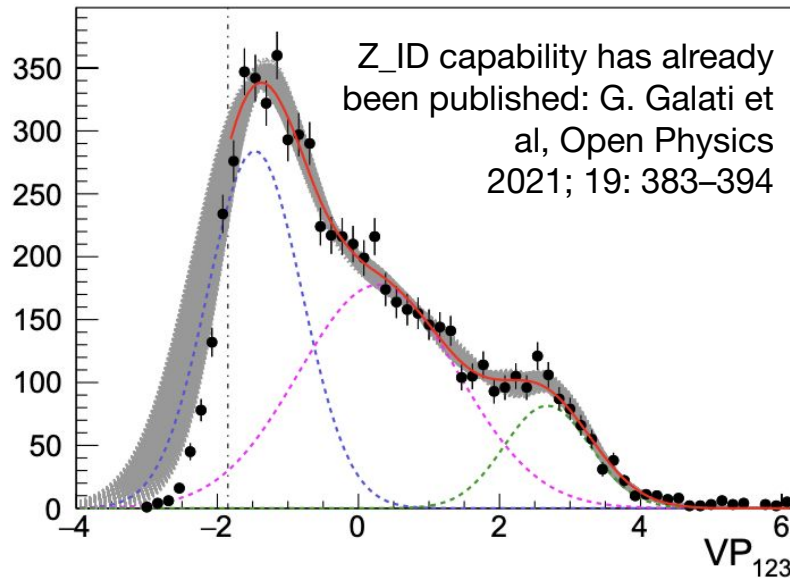
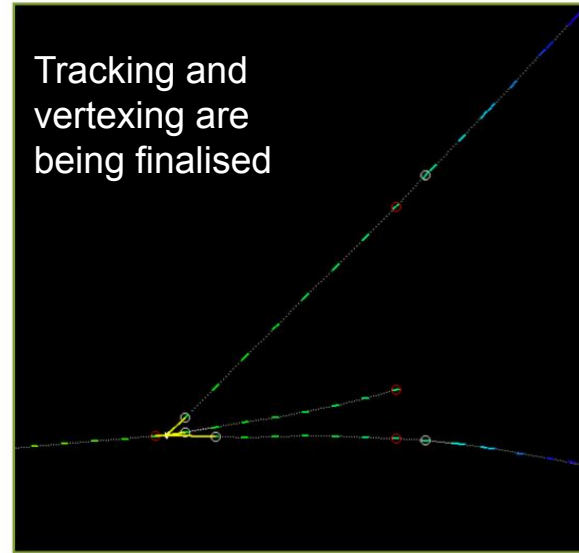


data from GSI 2019 data taking

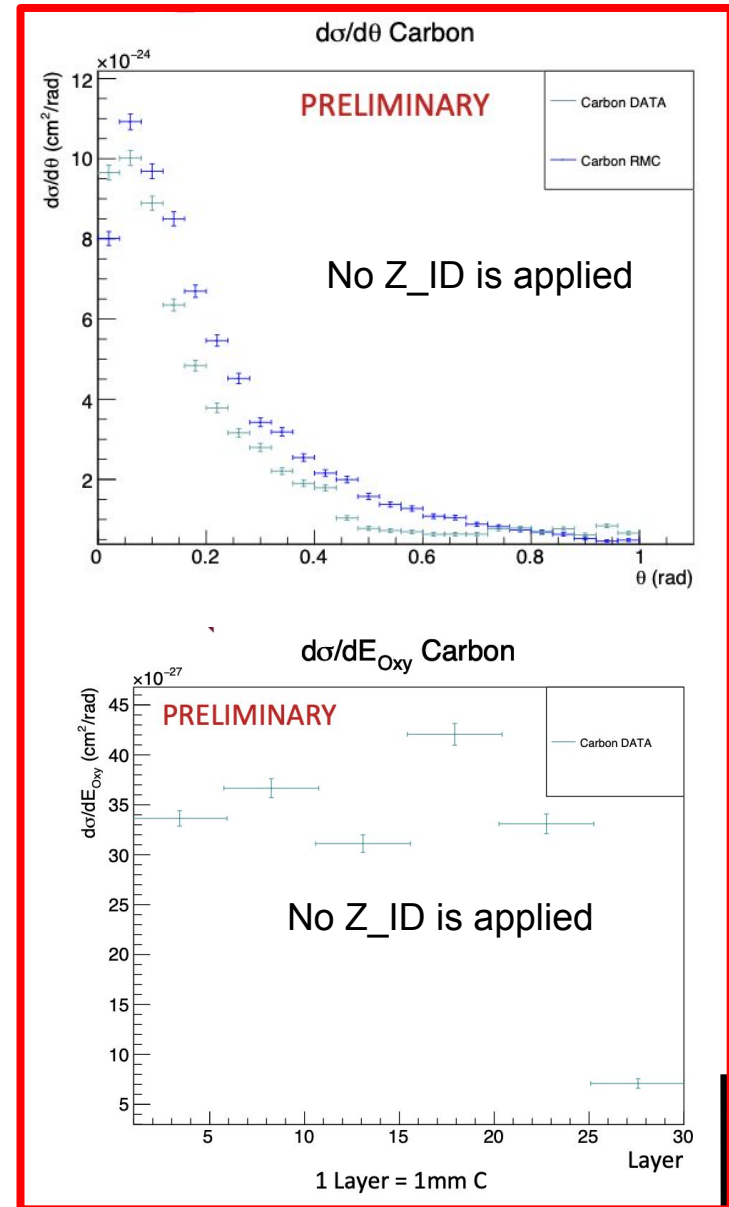
# CS are behind the corner!

In 2019 four ECC (2 C, and 2 C<sub>2</sub>H<sub>4</sub>) were exposed to two different <sup>16</sup>O beams of 200 and 400 MeV/u kin energy

Tracking and vertexing are being finalised

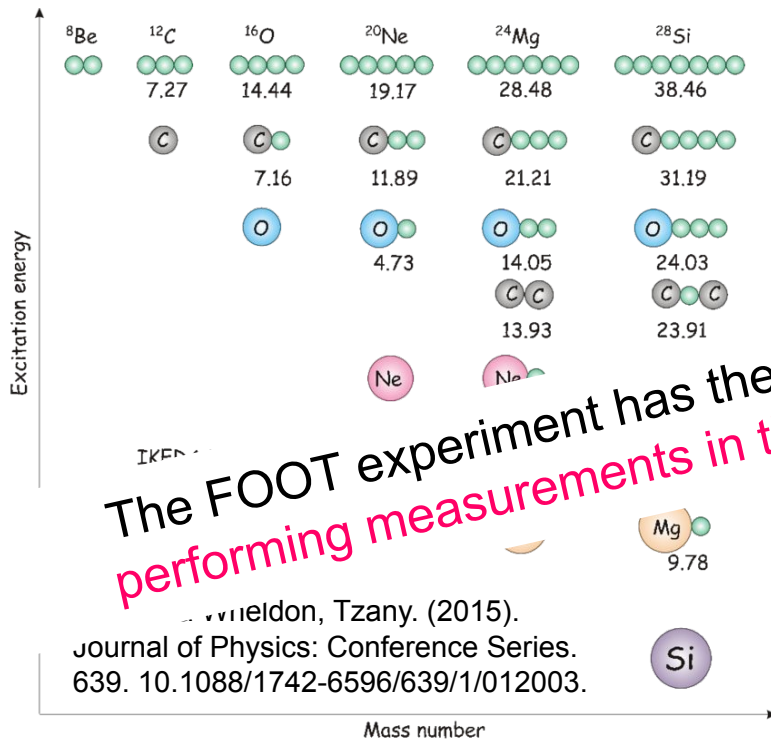


Total cross sections are already available!



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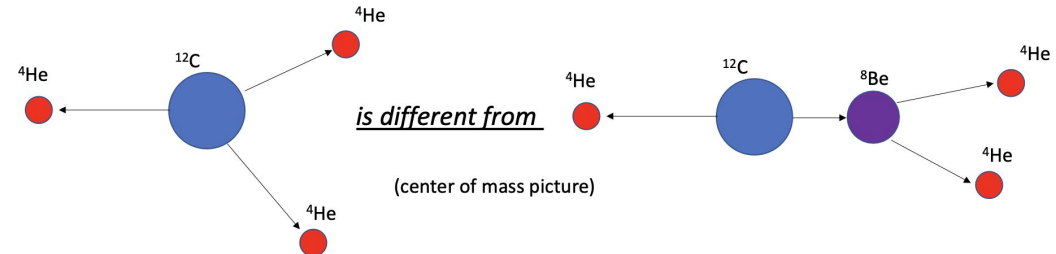
- ➔ Among several nuclear process of interest for PT and SRP applications, one process plays a significant role: “tendency of nucleons in a nucleus to form permanent or transient substructures” depending on the binding energy



The existence of preferential fragmentation channels like  $^{12}\text{C} \rightarrow 3\ ^4\text{He}$  and  $^{16}\text{O} \rightarrow 4\ ^4\text{He}$  is well experimentally established for  $E/A > 1\ \text{GeV/u}$ .

The FOOT experiment has the huge opportunity of studying such effect, performing measurements in the energy range btw 100 and 1000 MeV/u

Journal of Physics: Conference Series. 639. 10.1088/1742-6596/639/1/012003.

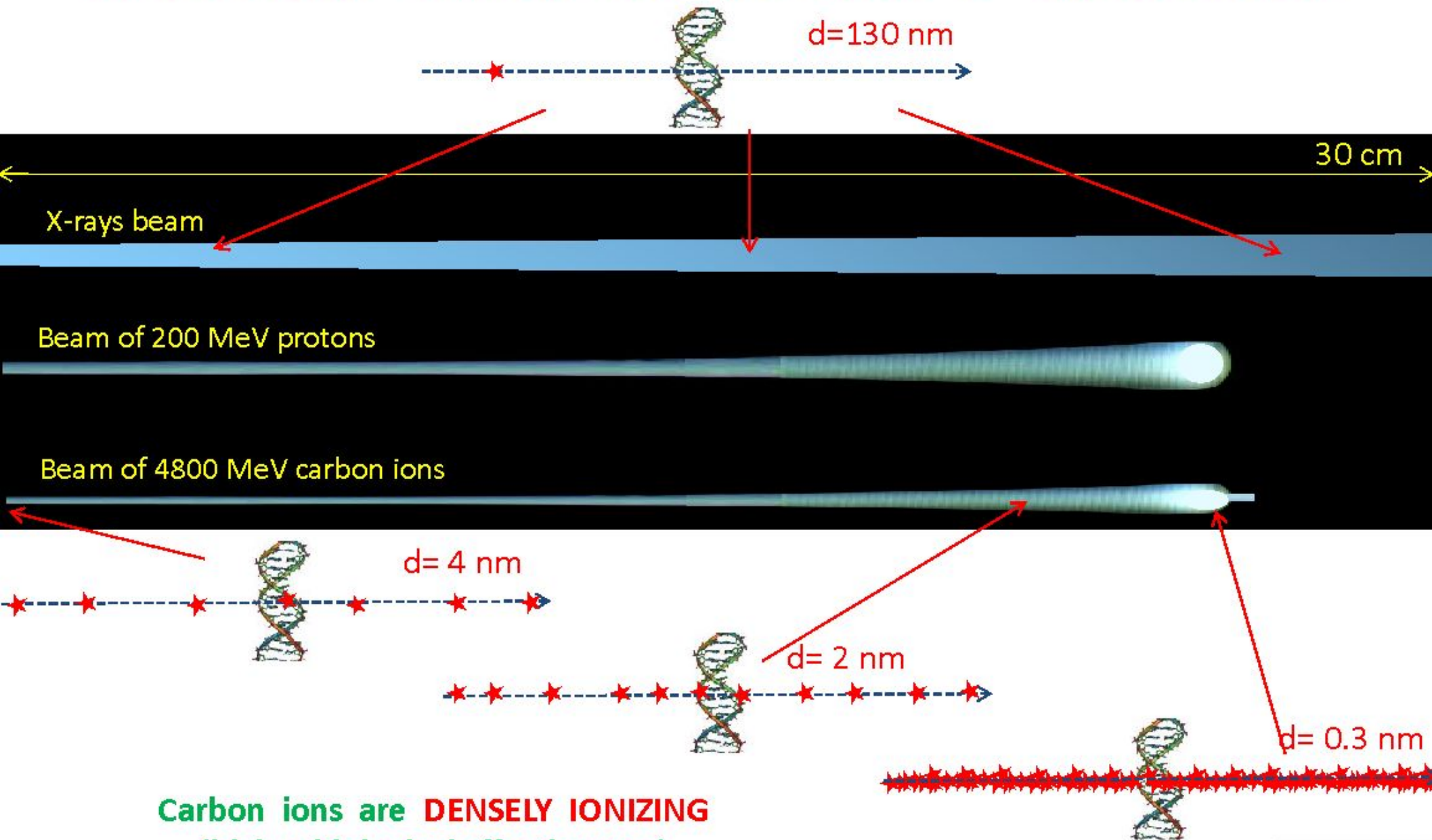


# Conclusions

- ➔ Interesting time ahead
  - The **FAIR (2025 - 2027) facility will provide access to unprecedented energies**
  - FOOT and FRACAS experiments are getting ready.. DDCS measurements are starting in 2023 (FOOT)
    - First attempts will aim for **ECC** & what can be done at sub-optimal resolution on M (no magnets, **focus on charge/position reconstruction**)
- ➔ Another ‘yet-untackled’ challenge: **neutrons!**
  - Play a major role in both PT & SRP but have eluded attempts for a ‘efficient’ reconstruction/backtracking... need dedicated manpower/funds [we have the detector ‘in our minds’ :)]
- ➔ Beside PT & SRP: the case of O and C fragm into He is teaching us that we can provide exp. inputs **for nuclear model developments..**
  - Other ideas are welcomed!



# Carbon ions: 1. more favorable dose 2 'direct effects'



Carbon ions are **DENSELY IONIZING**  
(higher biological effectiveness)

Courtesy U.Amaldi



# "Typical" modeling of nuclear interactions:

Target nucleus description (density, Fermi motion, etc)



Glauber-Gribov cascade with formation zone



Generalized IntraNuclear cascade



Preequilibrium stage with current exciton configuration and excitation energy  
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)



Evaporation/Fragmentation/Fission model



$\gamma$  deexcitation

$t$  (s)

$10^{-23}$

$10^{-22}$

$10^{-20}$

$10^{-16}$

# Frag meas: thick target

A lot of integral measurements are already around..

Projectile Energy[MeV/N] Target

$^4\text{He}$	100, 180	C, Al, Cu, Pb
$^{12}\text{C}$	100, 180, 400	C, Al, Cu, Pb
$^{20}\text{Ne}$	100, 180, 400	C, Al, Cu, Pb
$^{28}\text{Si}$	800	C, Al, Cu, Pb
$^{40}\text{Ar}$	400	C, Al, Cu, Pb
$^{56}\text{Fe}$	400	C, Al, Cu, Pb
$^{126}\text{Xe}$	400	C, Al, Cu, Pb

HIMAC by Kurosawa et al.

$^{20}\text{Ne}$	337	C, A, Cu and U
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BEVALAC by Schimmerling et al.

$^{93}\text{Nb}$	272	Al, Nb
$^{93}\text{Nb}$	435	Nb

BEVALAC by Heilbronn et al.

$^4\text{He}$	155	Al
$^{12}\text{C}$	155	Nb

NSRL by Heilbronn et al.

$^4\text{He}$	160	Pb
$^4\text{He}$	180	C, H <sub>2</sub> O, steel, Pb

SREL by Cecil

$^{12}\text{C}$	200	H <sub>2</sub> O
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GSI by Günzert-Marx et al.

$^{12}\text{C}$	400	H <sub>2</sub> O
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GSI by Haettner et al.

Tentative & incomplete list

Courtesy of M. Durante

# Frag meas: thin target

A lot of measurements on thin target are already around.. but not wrt angle and energy

• Projectile	Energy[MeV/N]	Target
• $^4\text{He}$	135	C, Poly, Al, Cu, Pb
• $^{12}\text{C}$	135	C, Poly, Al, Cu, Pb
• $^{20}\text{Ne}$	135	C, Poly, Al, Cu, Pb
• $^{40}\text{Ar}$	95	C, Poly, Al, Cu, Pb
• $^{12}\text{C}$	290, 400	C, Cu, Pb
• $^{20}\text{Ne}$	400, 600	C, Cu, Pb
• $^{40}\text{Ar}$	400, 560	C, Cu, Pb
• $^4\text{He}$	230	Li, C, $\text{CH}_2$ , Al, Cu, Pb
• $^{14}\text{N}$	400	Li, C, $\text{CH}_2$ , Al, Cu, Pb
• $^{28}\text{Si}$	600	Li, C, $\text{CH}_2$ , Al, Cu, Pb
• $^{56}\text{Fe}$	500	Li, C, $\text{CH}_2$ , Al, Cu, Pb
• $^{86}\text{Kr}$	400	Li, C, $\text{CH}_2$ , Al, Cu, Pb
• $^{126}\text{Xe}$	400	Li, C, $\text{CH}_2$ , Al, Cu, Pb

RIKEN by Sato et al.

HIMAC Iwata et al.

HIMAC E

Tentative & incomplete list

# Available DDCS

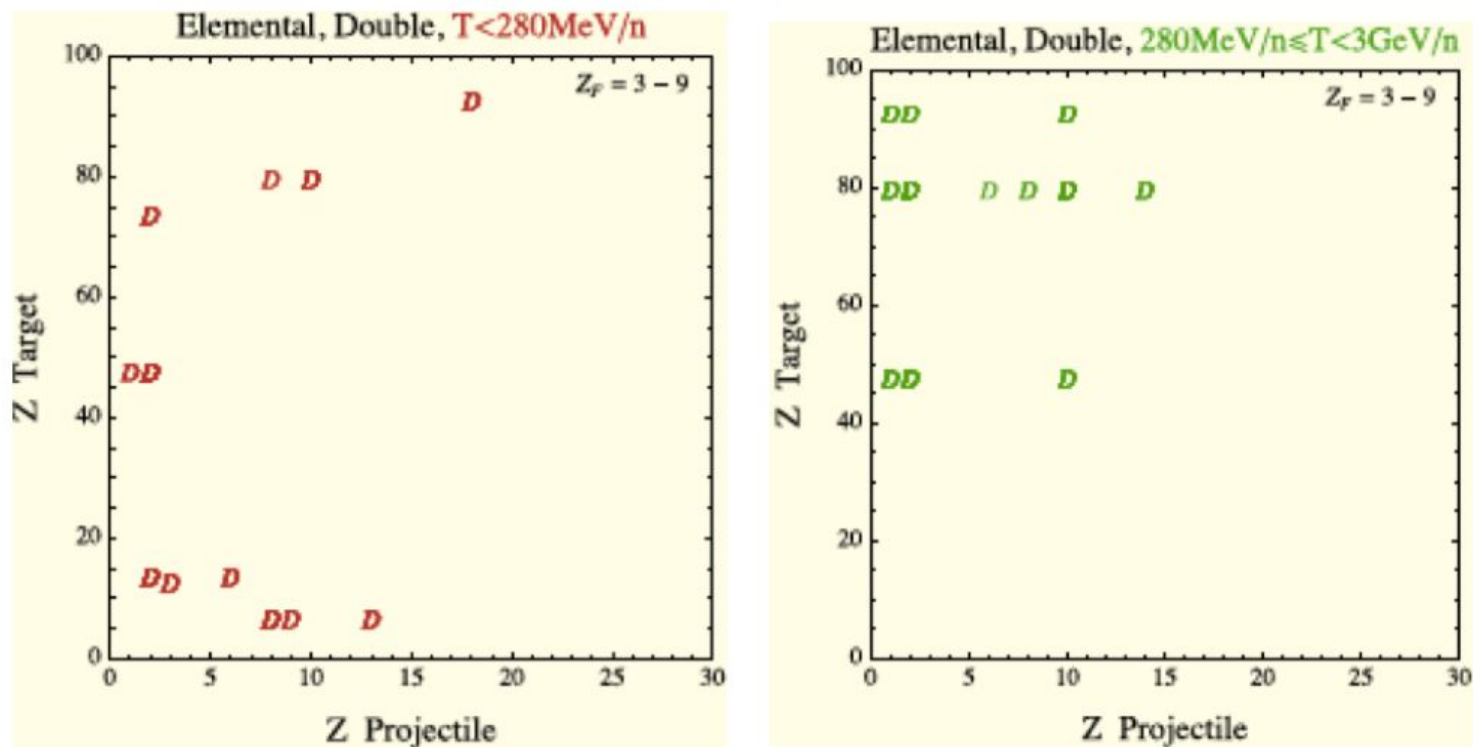
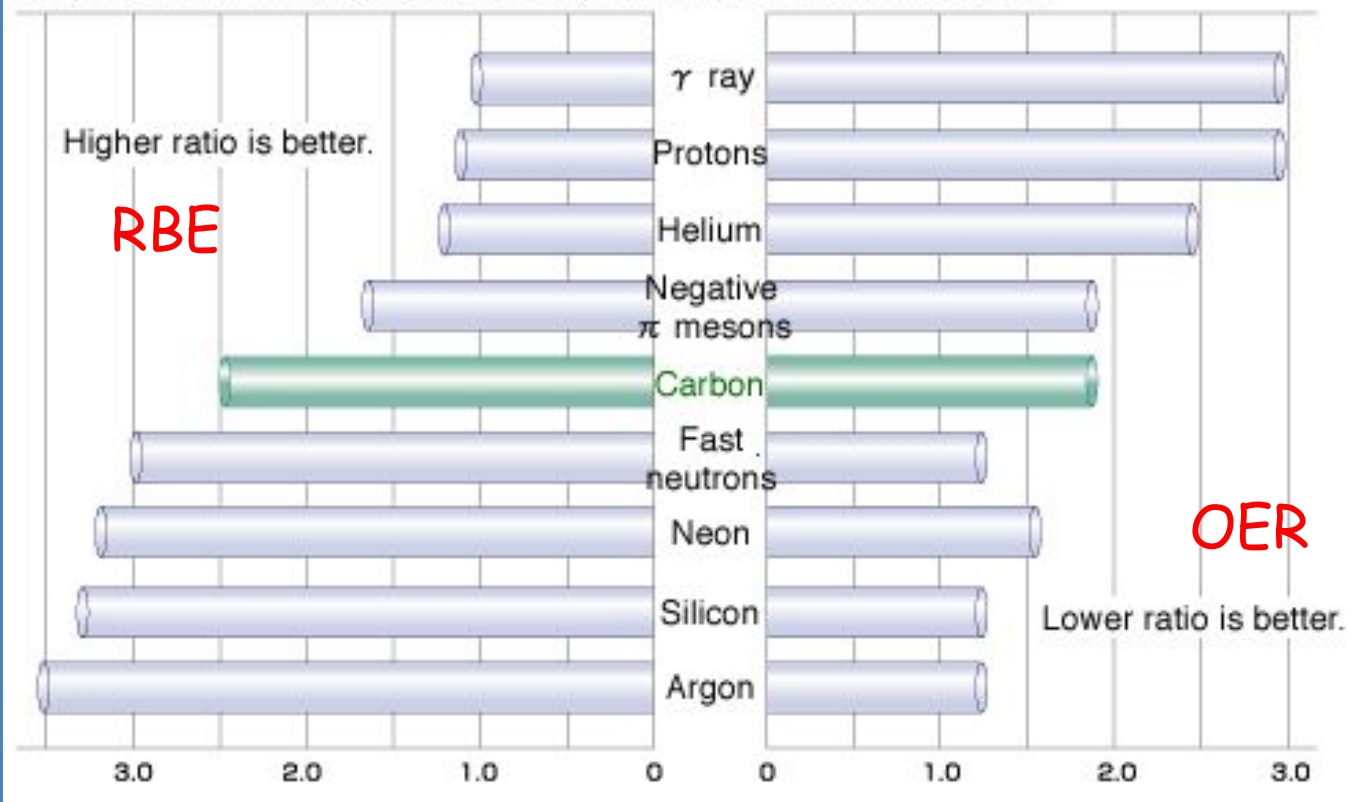


Figure 8 – Double differential cross sections available from literature for the production of medium-light fragments ( $Z_F = 3 - 9$ ). The data are shown as function of projectile and target charge  $Z$  and divided into two projectile energy ranges (below 290 MeV/u and between 290 MeV/u and 3 GeV/u).

# Radiations vs Biological effects

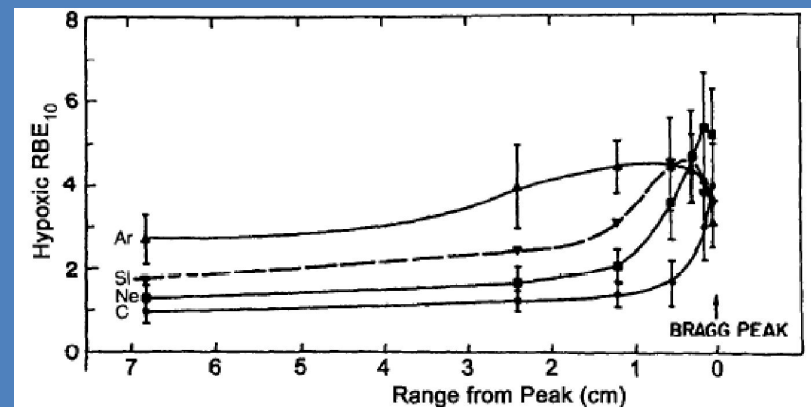


Relative biological effectiveness (RBE) and oxygen enhancement ratio (OER) of various radiation types



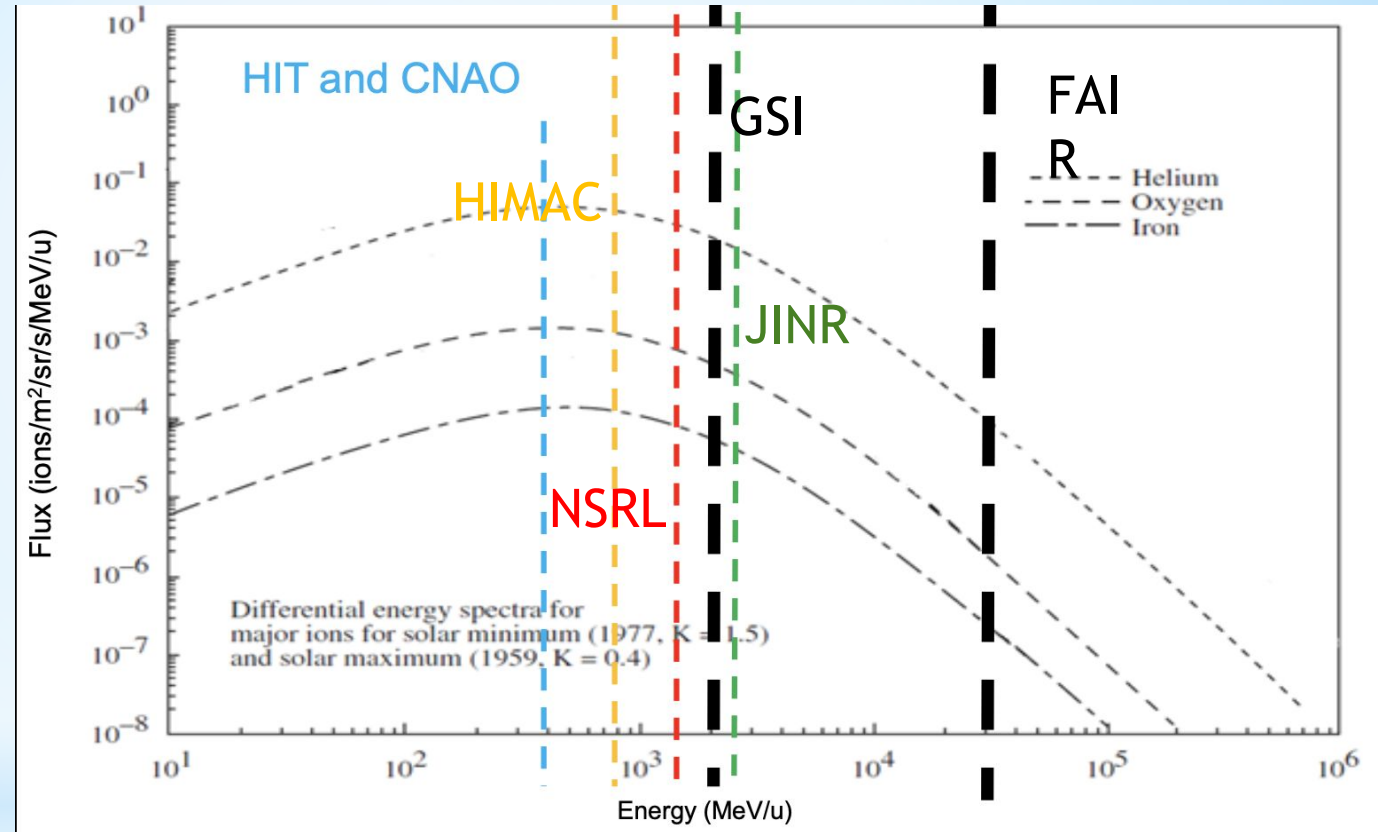
$^{12}\text{C} \rightarrow$  good compromise between RBE and OER.

Optimal RBE profile vs penetration depth position.



# On Earth exp: where and what?

- ✓ Dose attenuation experiment behind shielding materials
- ✓ Fragmentation cross sections, measurement, if possible double differential

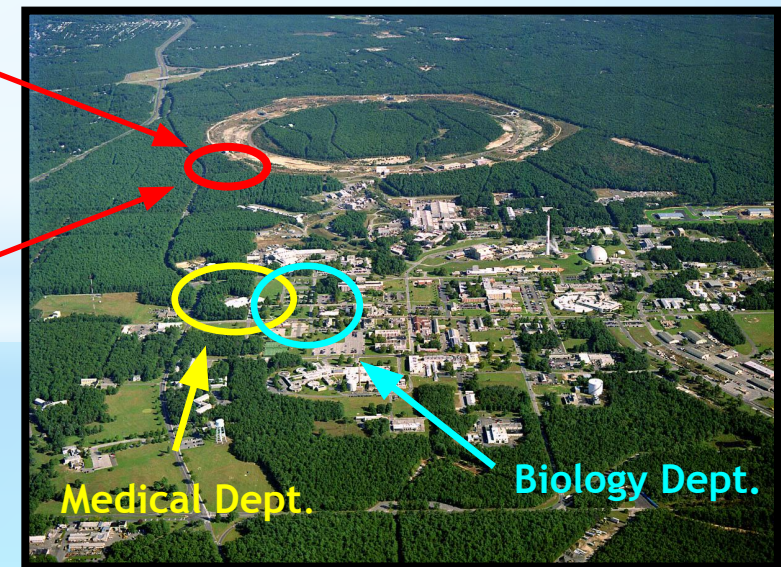
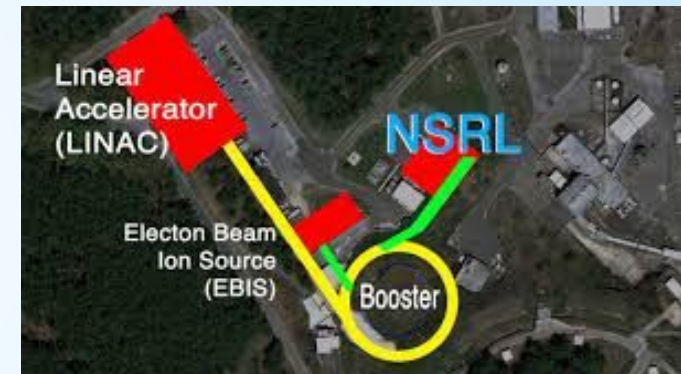


Few facilities provides the needed beam to explore GCR. Some are particle therapy treatment center: therapeutic beams have ~ same energy and ions of GCR!!!

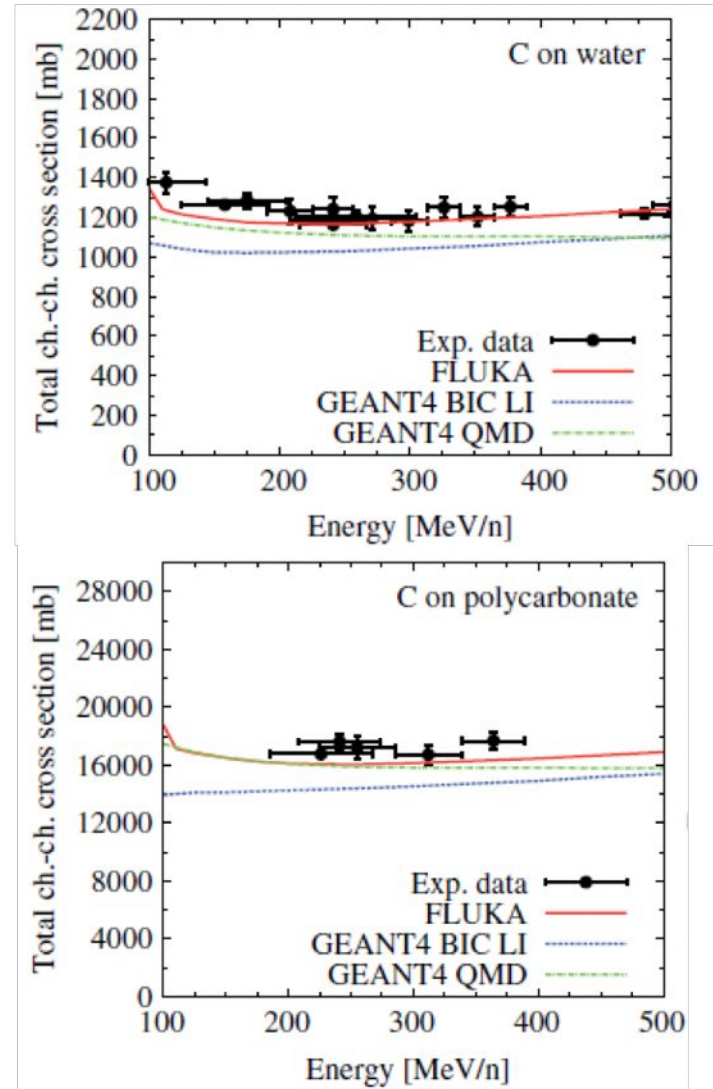
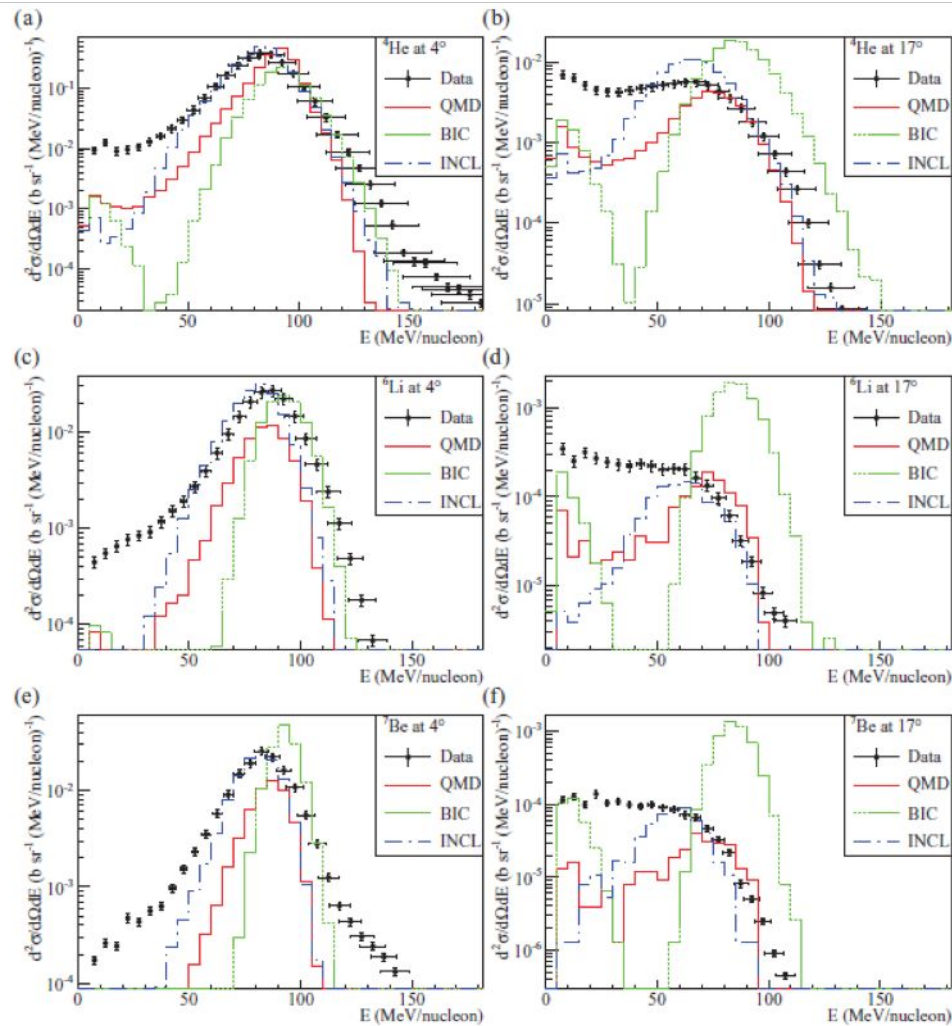


# NASA Research Programs @BNL

## NASA Space Radiation Health Program at the Brookhaven National Laboratory, Upton, NY



# DDCS data - MC agreement





# The challenge(s)

- The importance of a good charge separation / mass resolution:

$^{12}\text{C}$  ions on thin Au target..

