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

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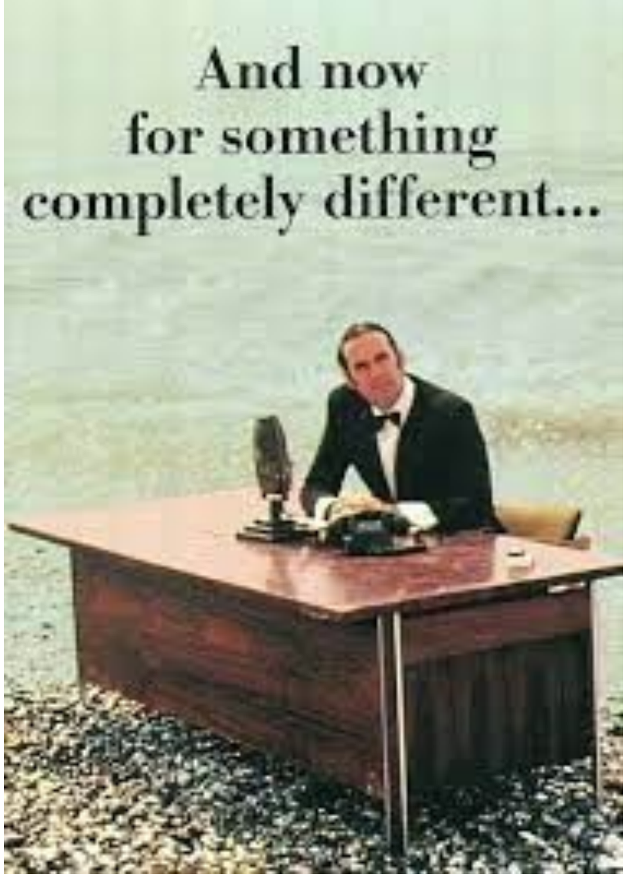
STRONG-2020 Annual Meeting

Dipartimento di Scienze di Base e Applicate per l'Ingegneria
Sapienza Università di Roma

Physics applications?



Physics applications?

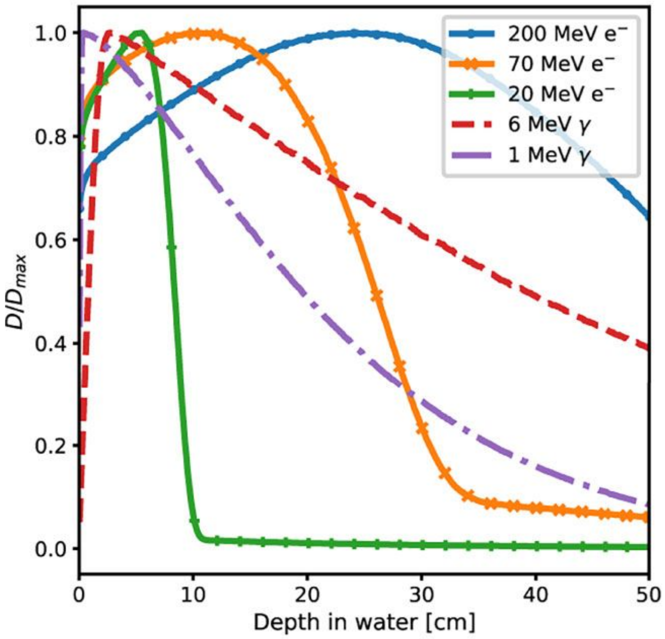
- ➡ There are really many many possible applications of hadronic/nuclear physics… Had not time to make an overview of all the possibilities… **Will focus, in this talk, on two main topics**:
  - **Particle Therapy**: use of protons / heavier ions to treat cancer via the 'External Beam Radio Therapy' 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..

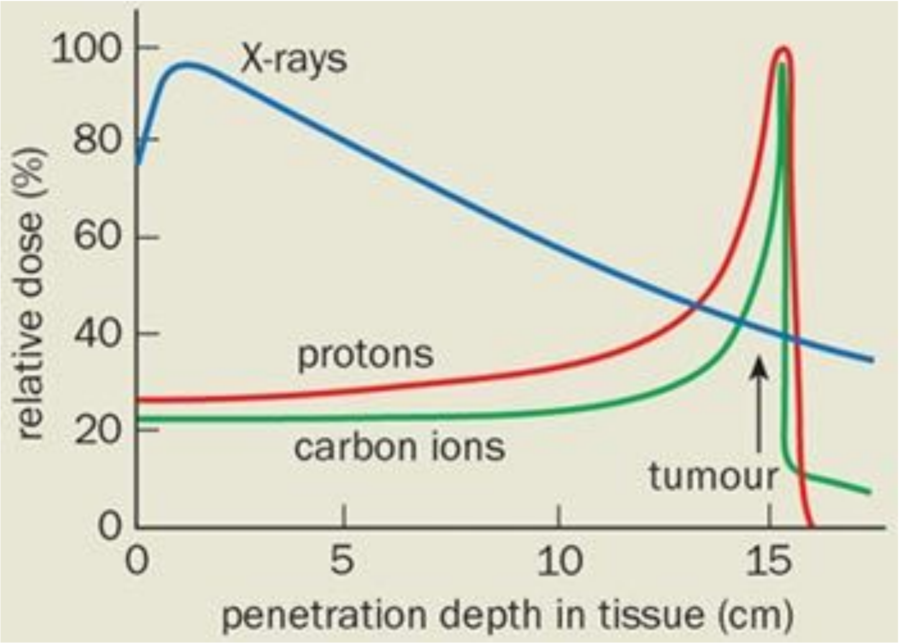
Direct link with strong interactions? uhmm… :)

Monte Carlo sims, data analysis techniques, detectors!

Charged nuclei in PT

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





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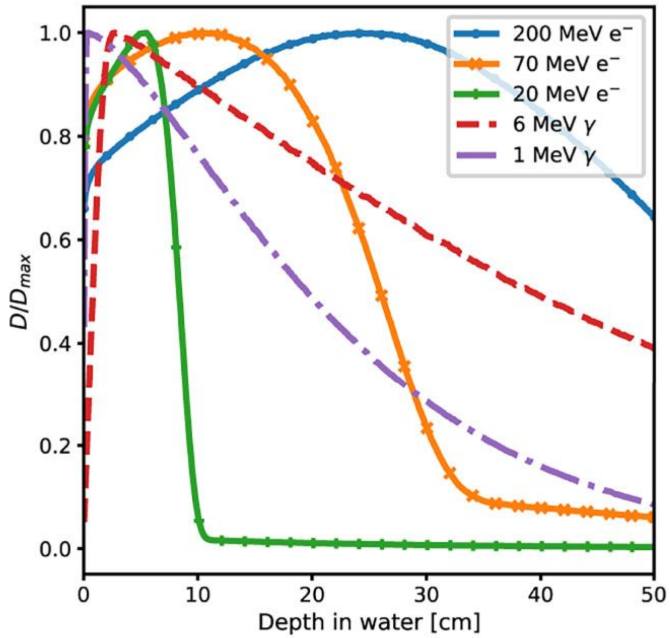
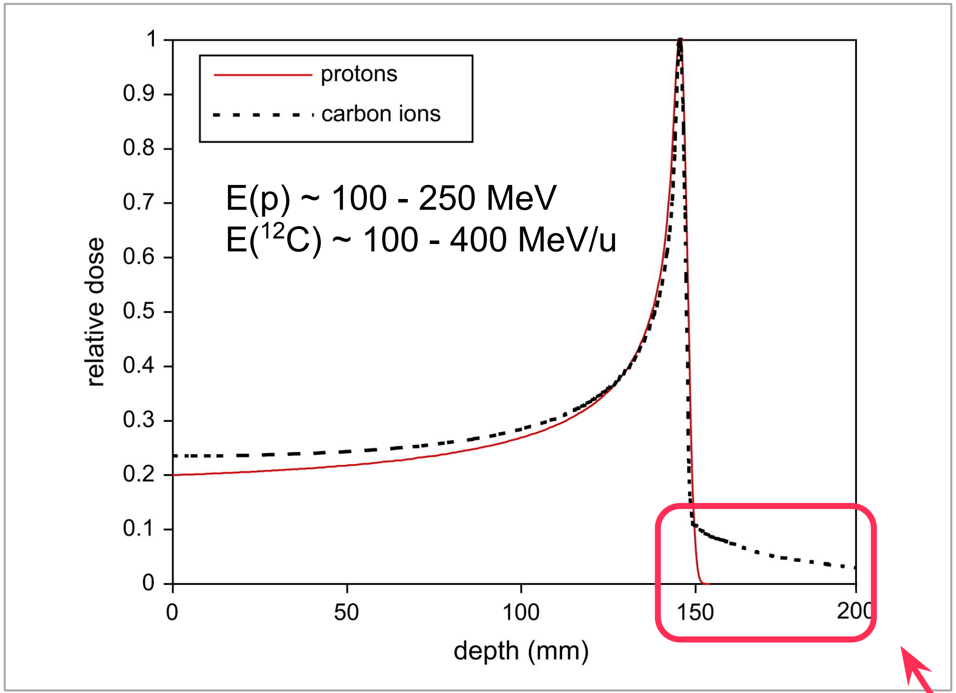
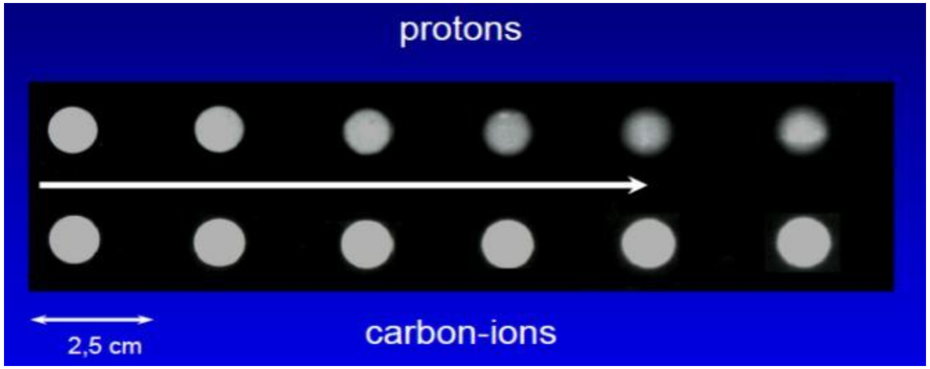




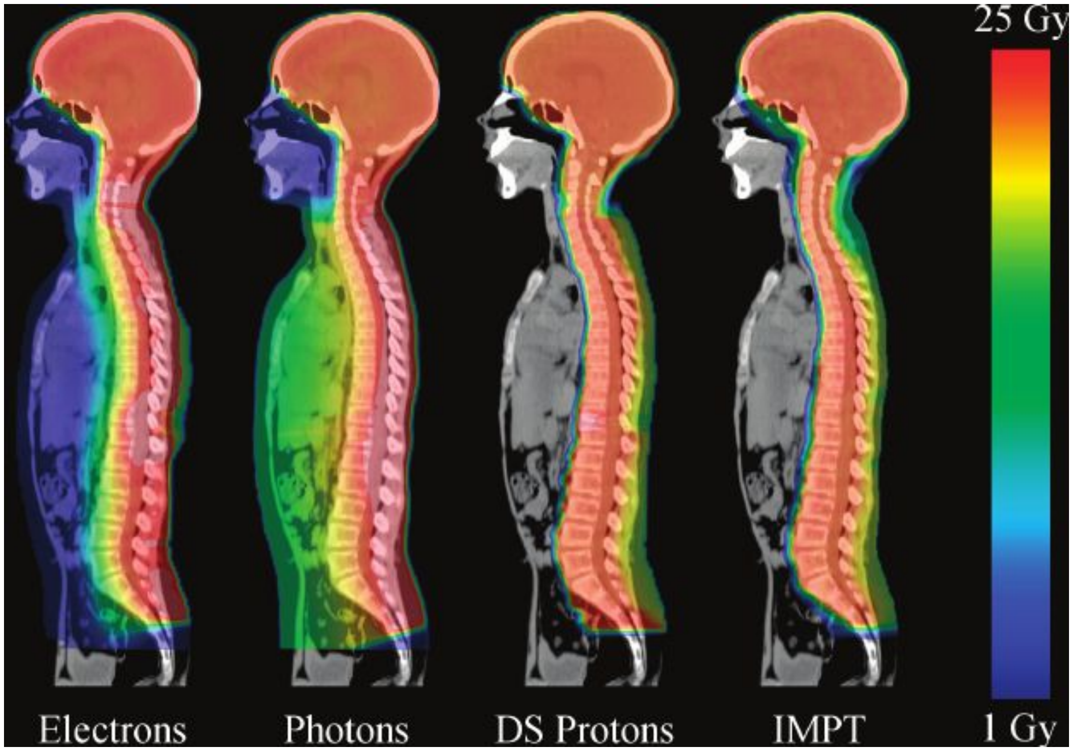


Protons are easier to accelerate…
but suffer from larger MS interactions..

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

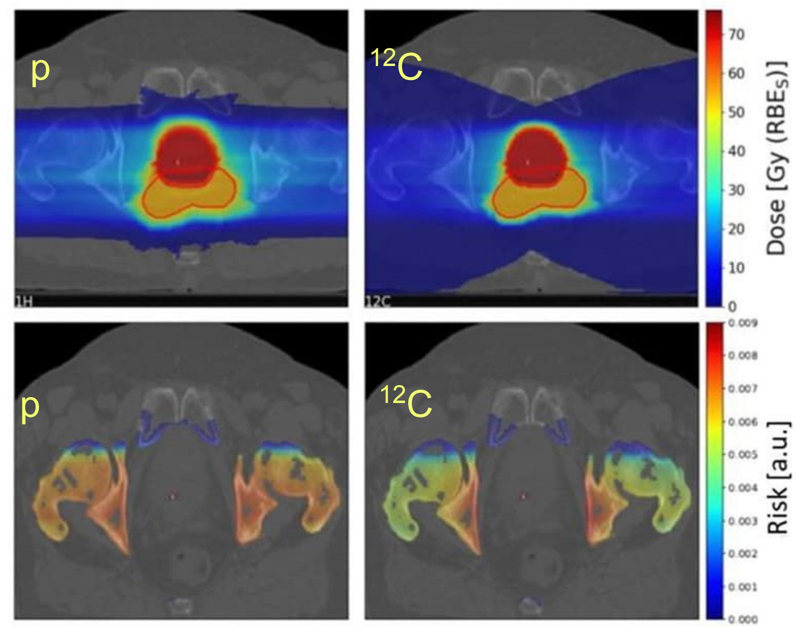
PT with p & I

- 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.

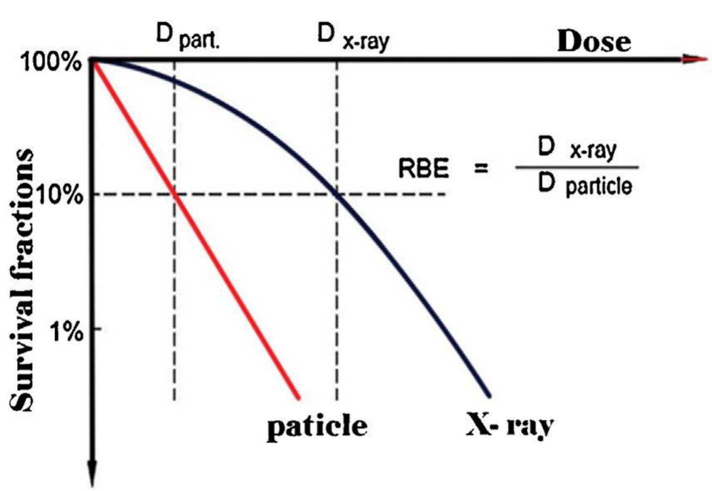


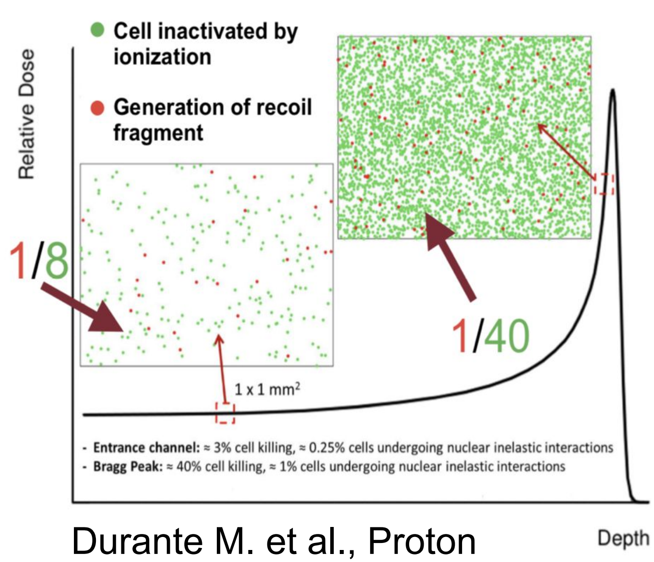
(Courtesy: CC BY 4.0/*Med. Phys.* 10.1002/mp.15805)

- 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}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.





Durante M. et al., Proton radiobiology (2015)

$$p + x \rightarrow p + \sum_i x_i$$

$T_{x_i} << T_p$

$\left(\frac{dE}{dx}\right)_x >> \left(\frac{dE}{dx}\right)_p$

→ Target fragments have **high RBE** values

In clinical practice protons RBE = 1.1

The particles produced in target **fragmentation** are one of the causes contributing **(~10%)** to the increase of proton RBE;

Ions… and ‘p-induced’ fragm.

- ➡ Ions can be either projectiles or targets in PT
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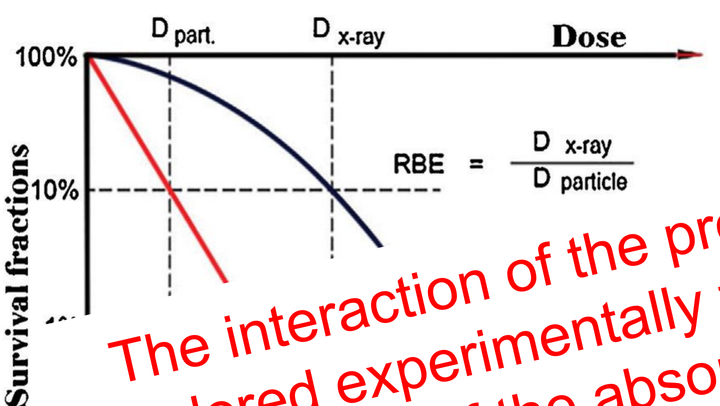

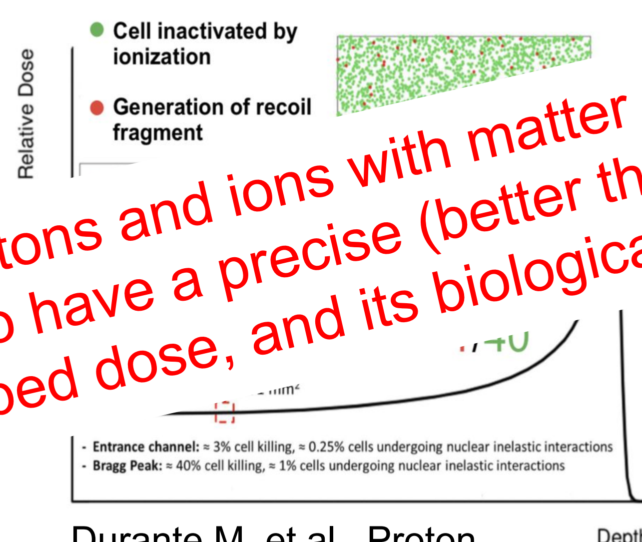

Durante M. et al., Proton radiobiology (2015)

The interaction of the protons and ions with matter has to be carefully explored experimentally to have a precise (better than 1% relative unc.) control of the absorbed dose, and its biological effectiveness!

In clinical practice protons RBE = 1.1

The particles produced in target **fragmentation** are one of the causes contributing **(~10%)** to the increase of proton RBE;

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

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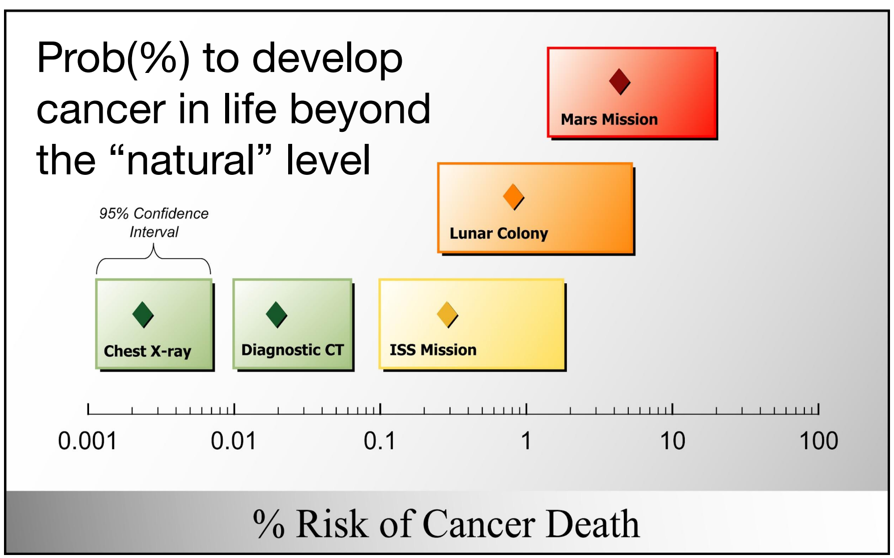
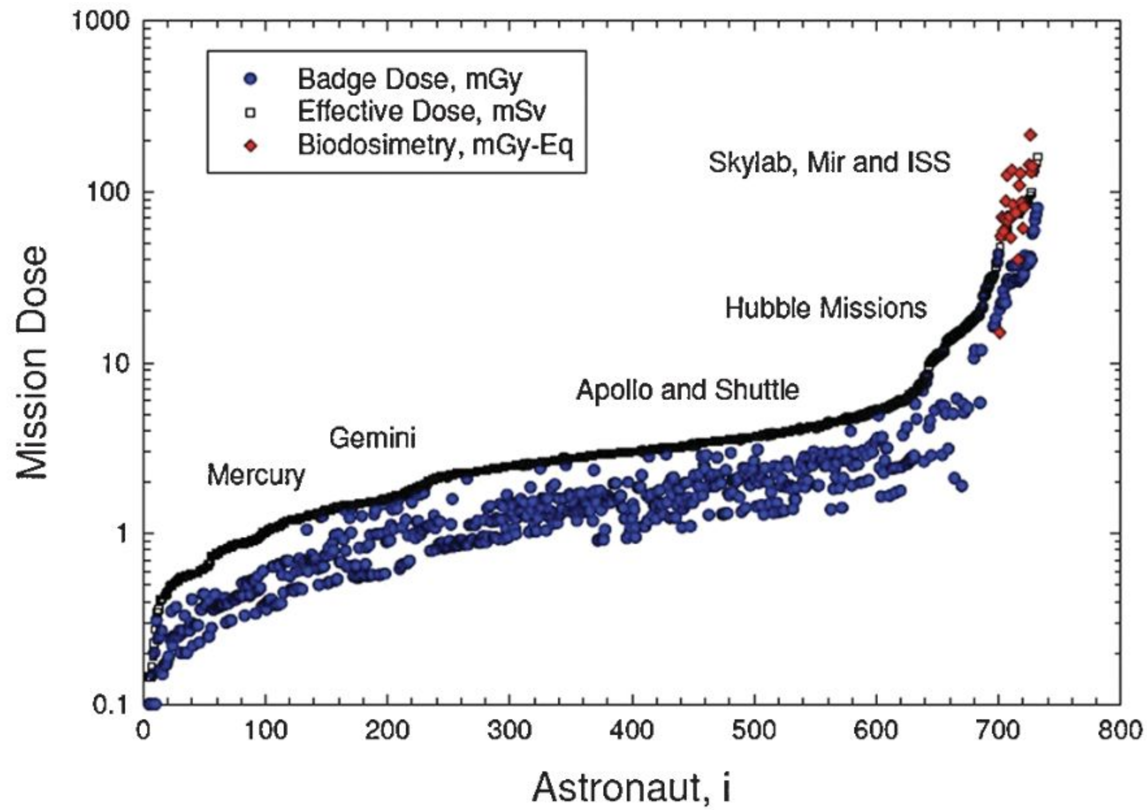
Review

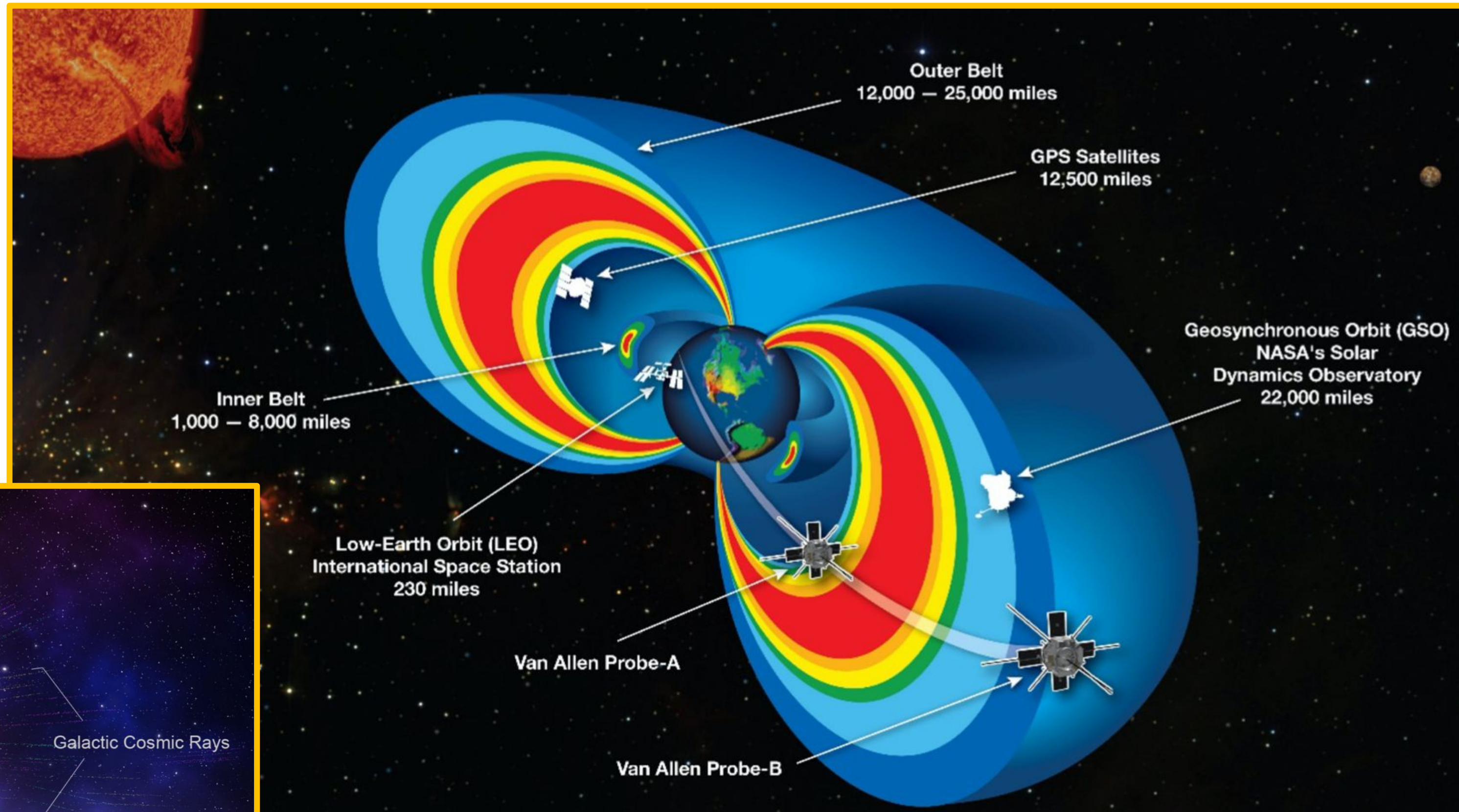
Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit

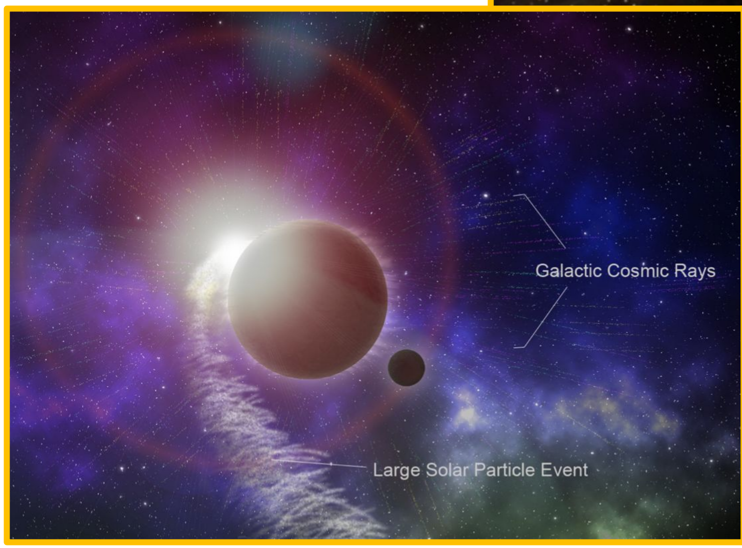
Jeffery C. Chancellor [1,2], Graham B. I. Scott [1,3] and Jeffrey P. Sutton [1,4,*]





The SRP environment





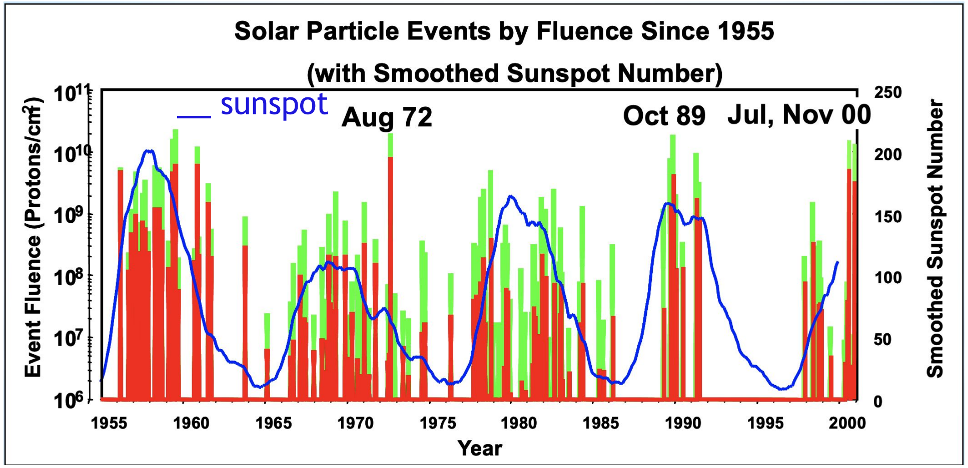
- Galactic Cosmic Rays GCR (all ions)
- Solar Particle Events SPE (mainly protons)
- Trapped particles (protons and electrons)
- Albedo radiation (electrons, protons, neutrons)

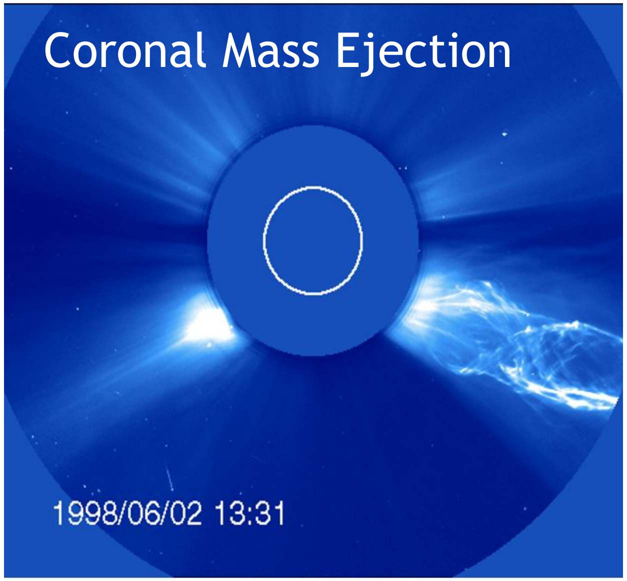
SPEs …

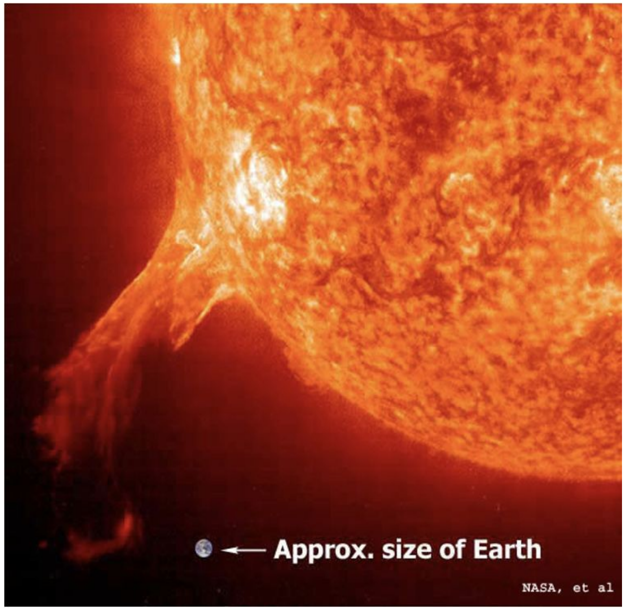
Solar Particle Events :
sudden emission by the Sun

Flux: up to ~10^{10} particles/cm^2 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.







.. and GCR spectra

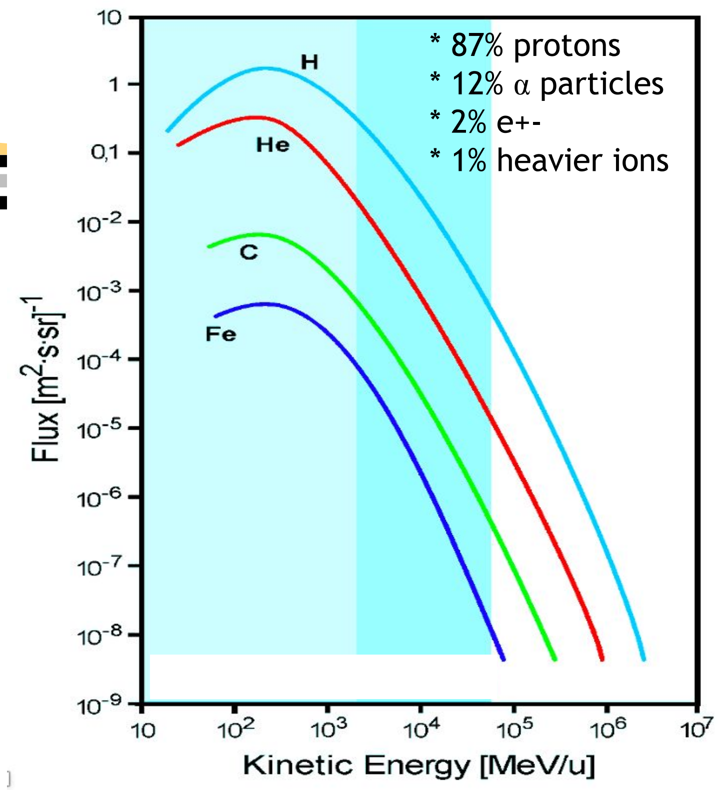
Galactic Cosmic Ray: continuous isotropic flux

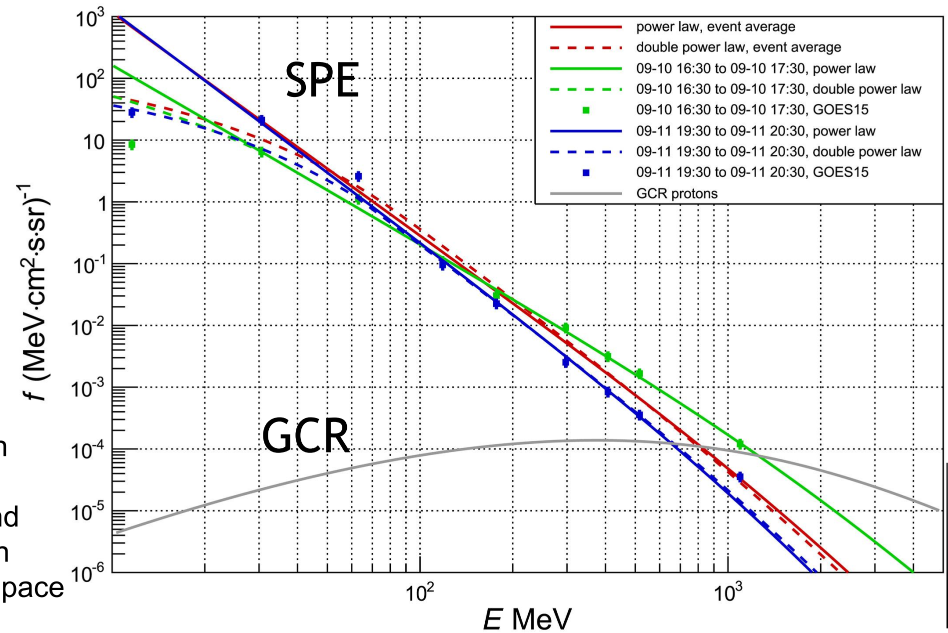
Spectrum: 90% protons, 10% heavier ions (~^{4}He), energy peaked at 1 GeV/nucleon

Flux: constant in time, isotropic, few particles/cm^2

Dose: order of ~1 mSv/d in outer space (1 year dose on Earth)

Penetrating particles, need heavy shielding to be stopped

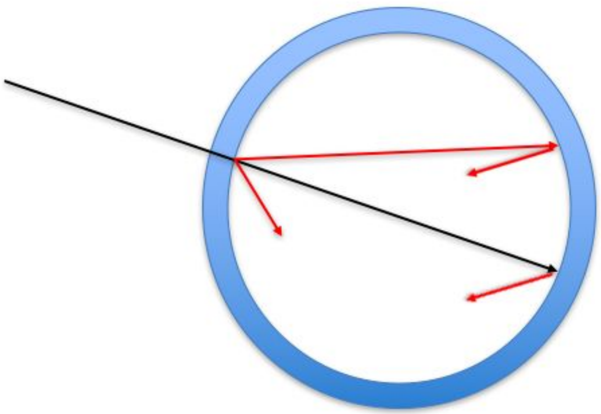


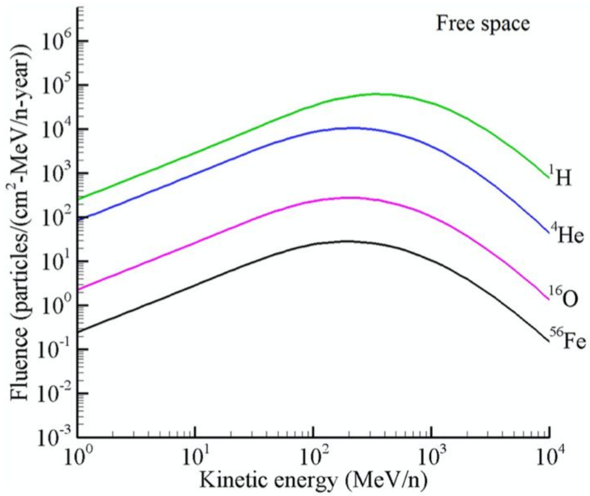


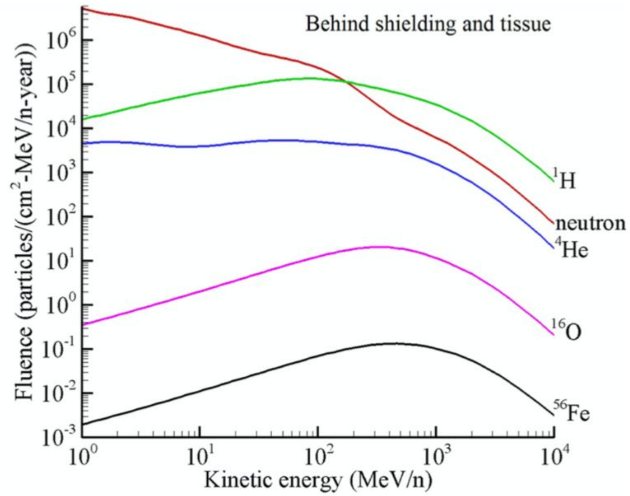
The Solar Particle Event on 10–13 September 2017: Spectral Reconstruction and Calculation of the Radiation Exposure in Aviation and Space

Space Weather, Volume: 16, Issue: 8, Pages: 977-986, First published: 17 July 2018, DOI: (10.1029/2018SW001921)

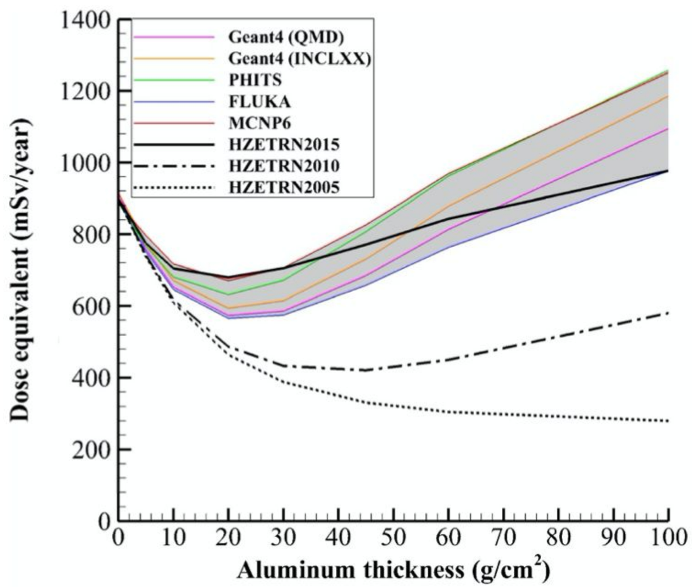
Goal: shielding design

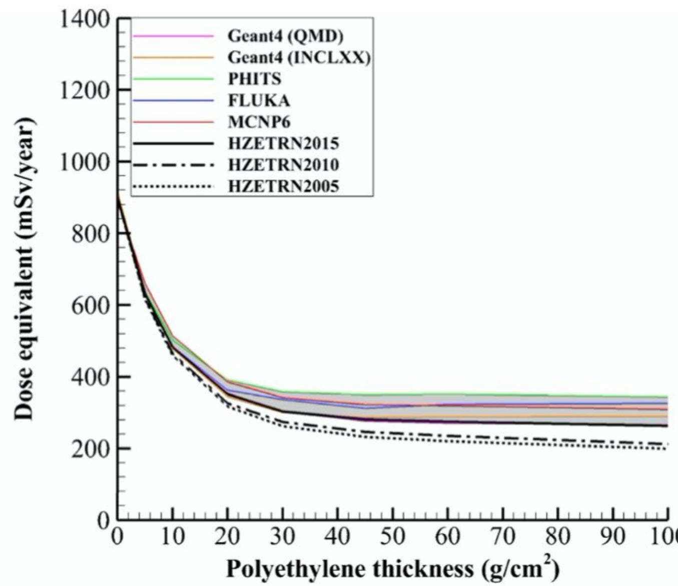






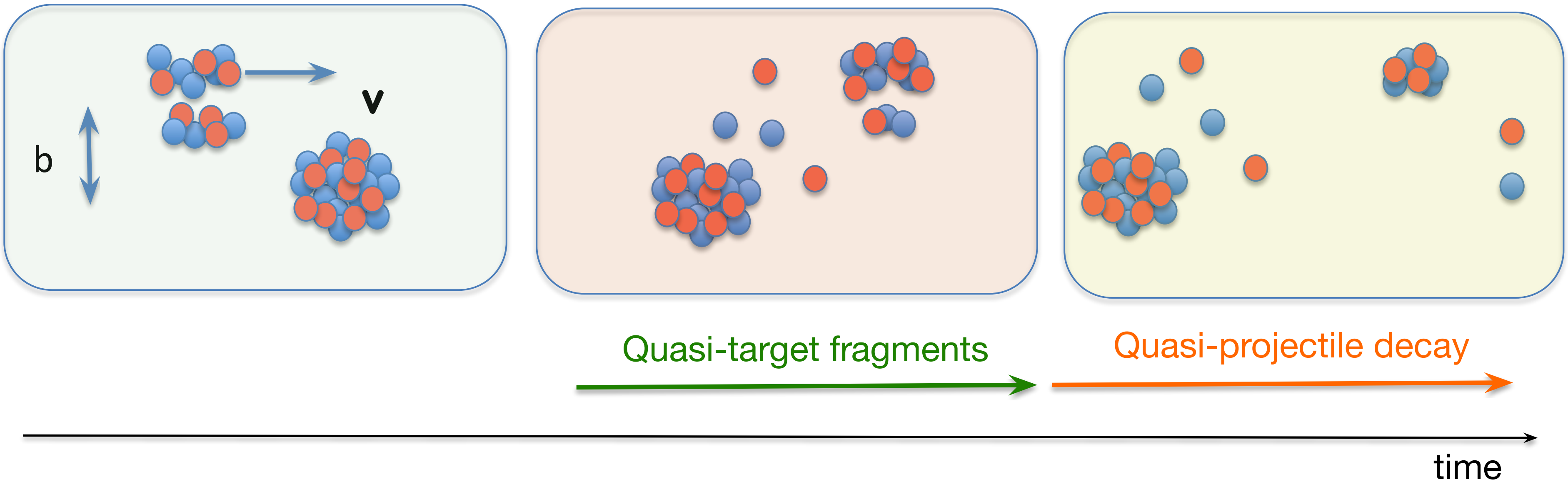
Transport codes indicate that the strategy of “the more the better” does not always work in space.





The ‘underlying’ physics..

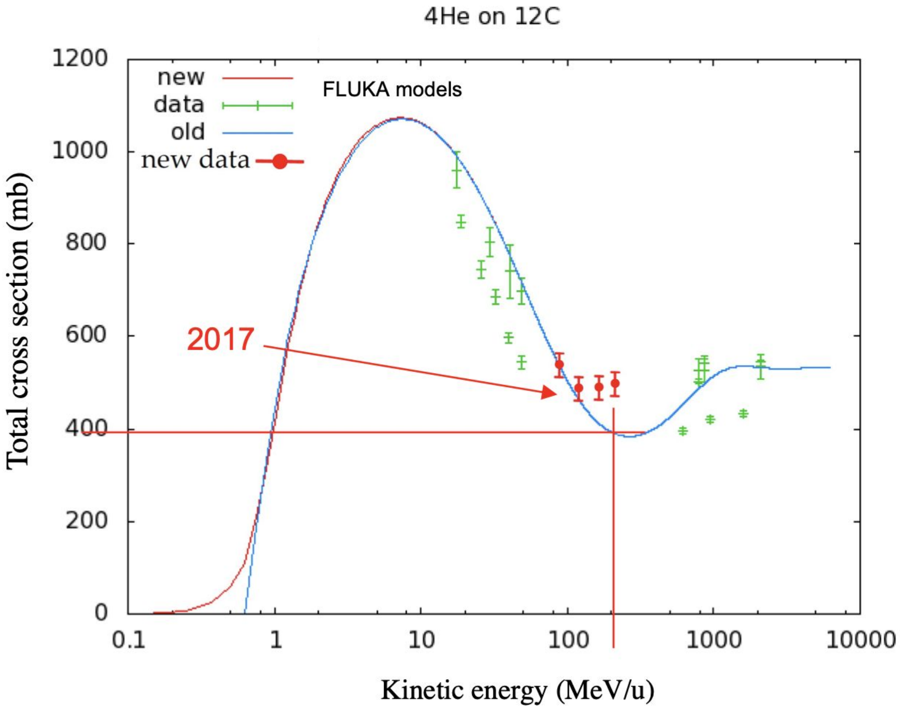
The abrasion - ablation paradigm

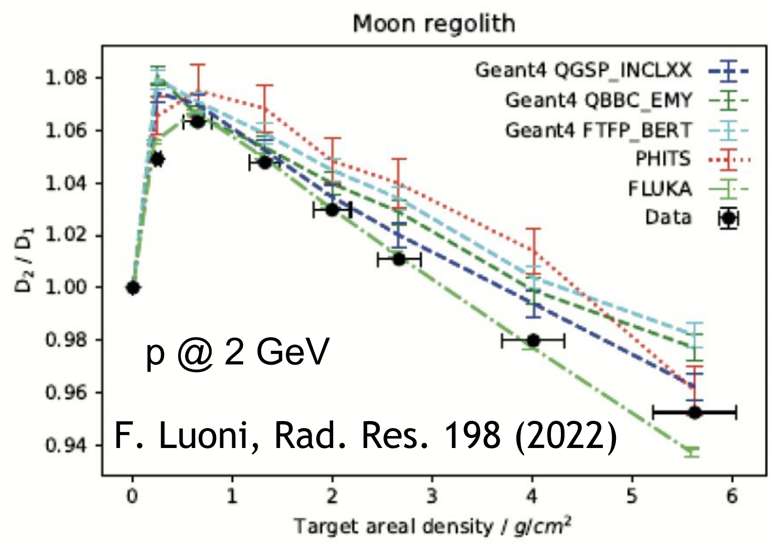


- Fragments from quasi-projectile have $V_{frag} \sim V_{beam}$ and narrow emission angle. Longer range then beam
- The other fragments have wider angular distribution but lower energy. Usually light particles (p,d,He)
- The dose beyond the distal part comes from the quasi projectile contribution. Wide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

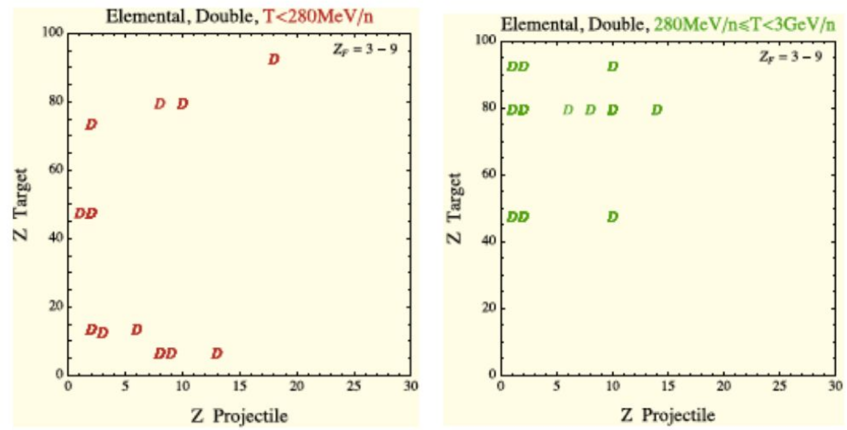
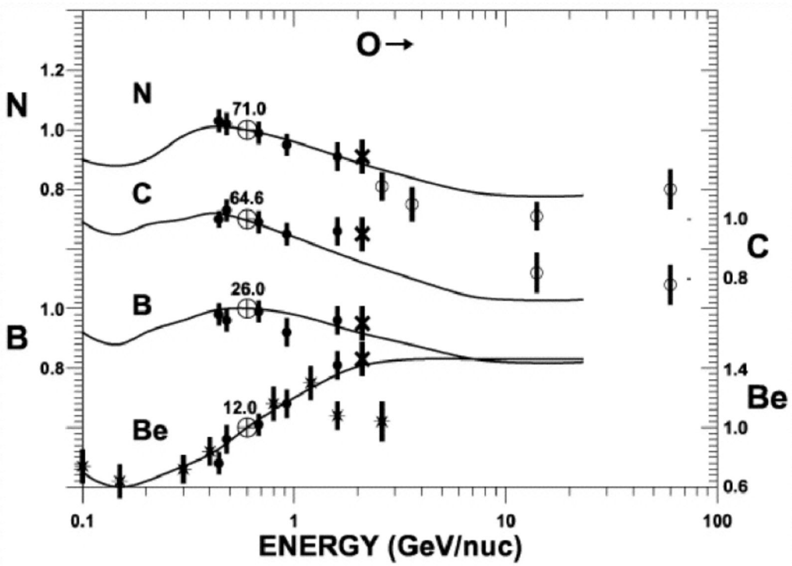


Figure 8 – Double differential cross sections available from literature for the production of medium-light fragments ($Z_F = 3 - 9$). The data are shown as function of projectile and target charge Z and divided into two projectile energy ranges (below 290 MeV/u and between 290 MeV/u and 3 GeV/u).

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



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

Integrated for Z<5 [2]

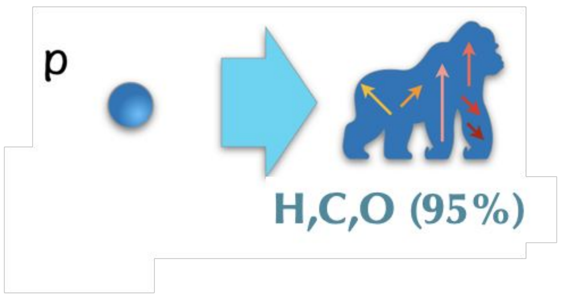
[1] https://doi.org/10.1103/PhysRevLett.107.032502
[2] https://doi.org/10.1103/PhysRevC.83.034909
[3] https://doi.org/10.1016/0168-583X(96)00325-4
[4] https://iopscience.iop.org/article/10.1086/344051/

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

p induced fragmentation..

- ➡ much tougher! Fragments produced @ E of interest for PT have energies/ranges of ~ μm

Direct kinematic

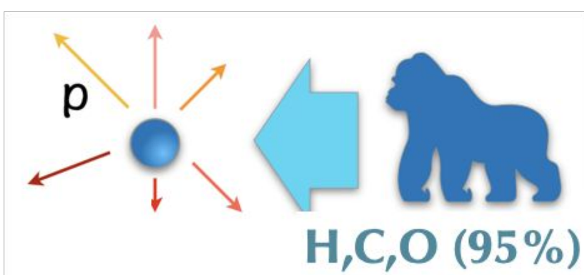


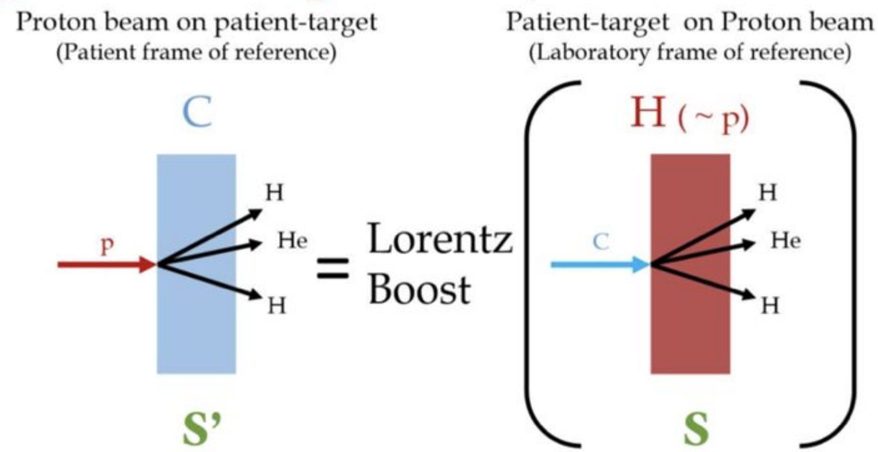
$$p(180MeV) + X(water) \rightarrow p' + X'_i$$

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

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

Inverse kinematic





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

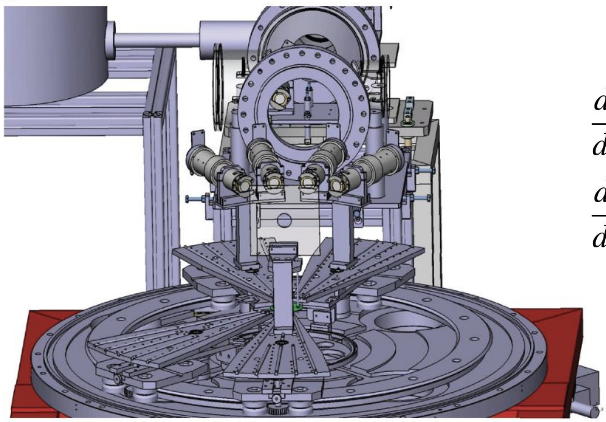
The challenge(s)

➡ Fragments separation… and cross section subtraction..

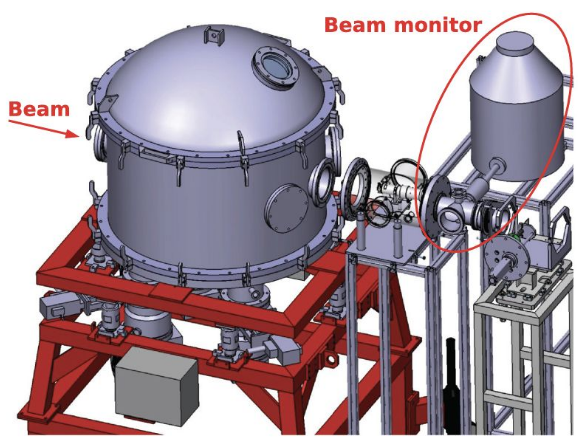
PHYSICAL REVIEW C **88**, 024606 (2013)

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

(a)

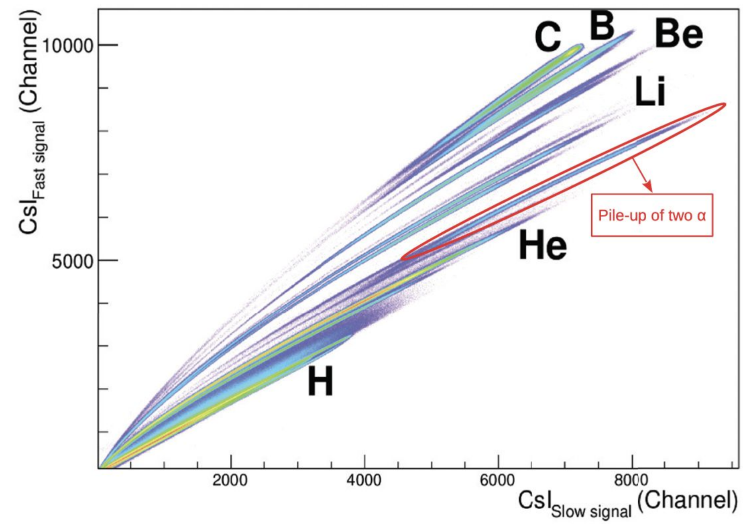


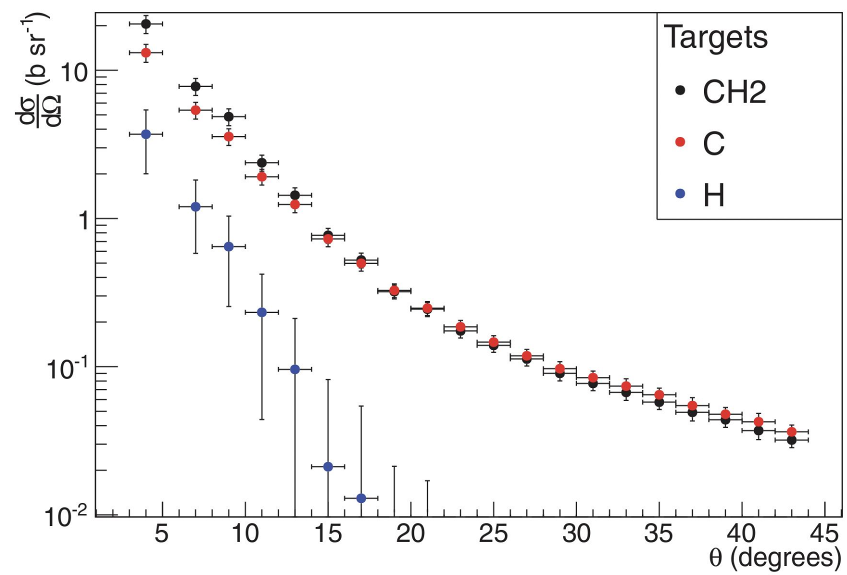
(b)



$$\frac{d\sigma}{d\Omega}(\mathrm{H}) = \frac{1}{2} \times \left(\frac{d\sigma}{d\Omega}(\mathrm{CH_2}) - \frac{d\sigma}{d\Omega}(\mathrm{C})\right),$$

$$\frac{d\sigma}{d\Omega}(\mathrm{O}) = \frac{1}{3} \times \left(\frac{d\sigma}{d\Omega}(\mathrm{Al_2O_3}) - 2 \times \frac{d\sigma}{d\Omega}(\mathrm{Al})\right).$$





The experimental quests

- FRACAS @ ARCADE

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

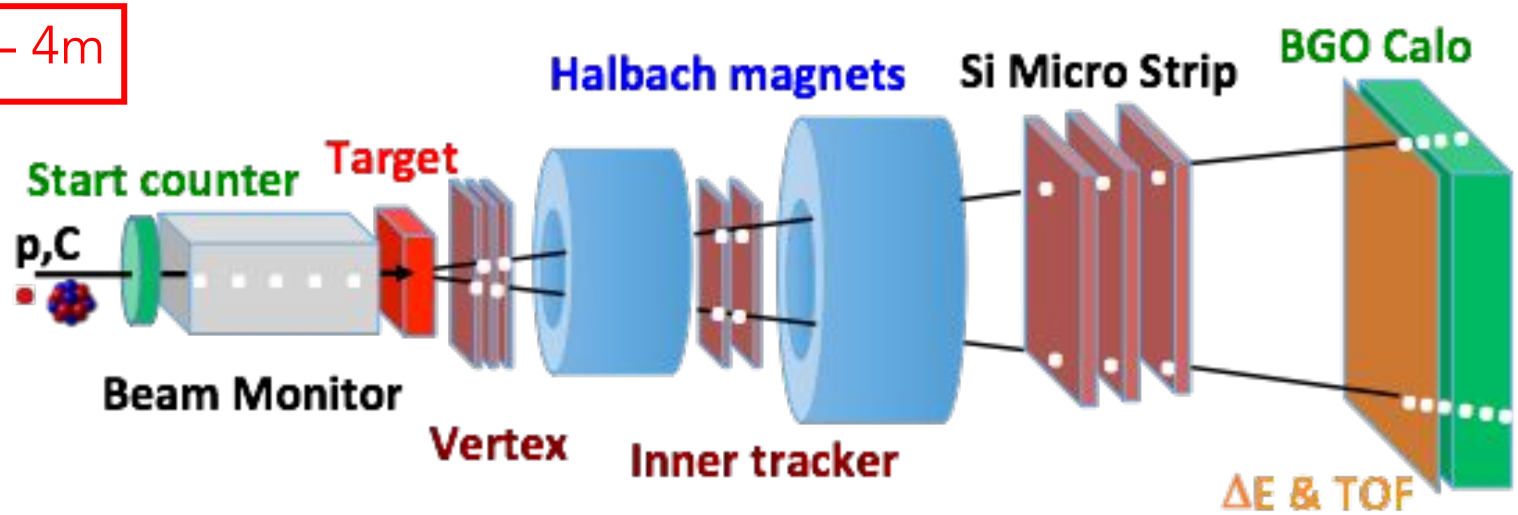
Double detector : emulsion setup for light fragments and electronic setup for Z>2 fragments

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 °



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

Target performances

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

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

FOOT physics plan

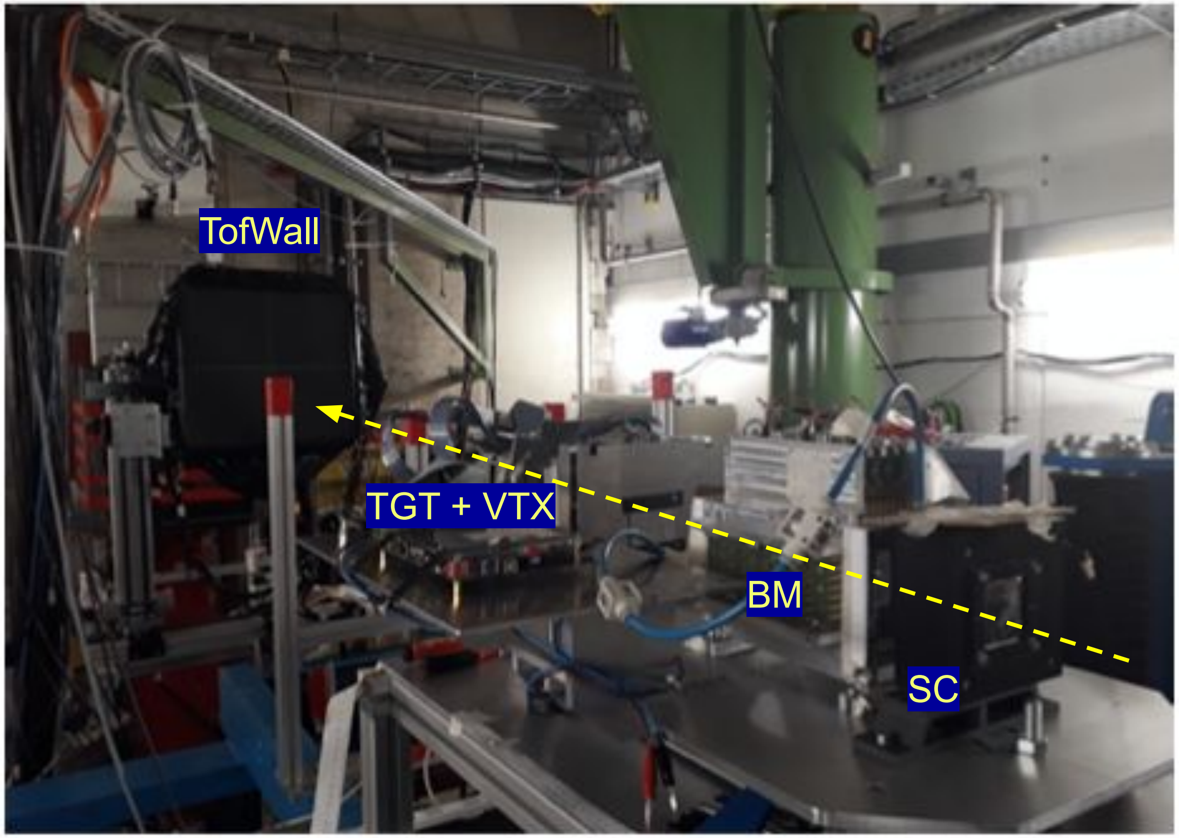
ALL data from the three targets C, C_2H_4 and PMMA are needed to obtain the elemental cross sections on C, O and H

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	^{12}C	C, C_2H_4	100-200	GSI, HIT, CNAO
Target Frag. PT	^{16}O	C, C_2H_4	100-200	GSI, HIT
Beam Frag. PT	^{12}C	C, C_2H_4, PMMA	200-350	GSI, HIT, CNAO
Beam Frag. PT	^{16}O	C, C_2H_4, PMMA	200-400	GSI, HIT
Beam Frag. PT	^{4}He	C, C_2H_4, PMMA	150-250	GSI, HIT
Rad. Prot.space	^{4}He	C, C_2H_4, PMMA	500-1000	GSI
Rad. Prot.space	^{12}C	C, C_2H_4, PMMA	500-1000	GSI
Rad. Prot.space	^{16}O	C, C_2H_4, PMMA	500-1000	GSI

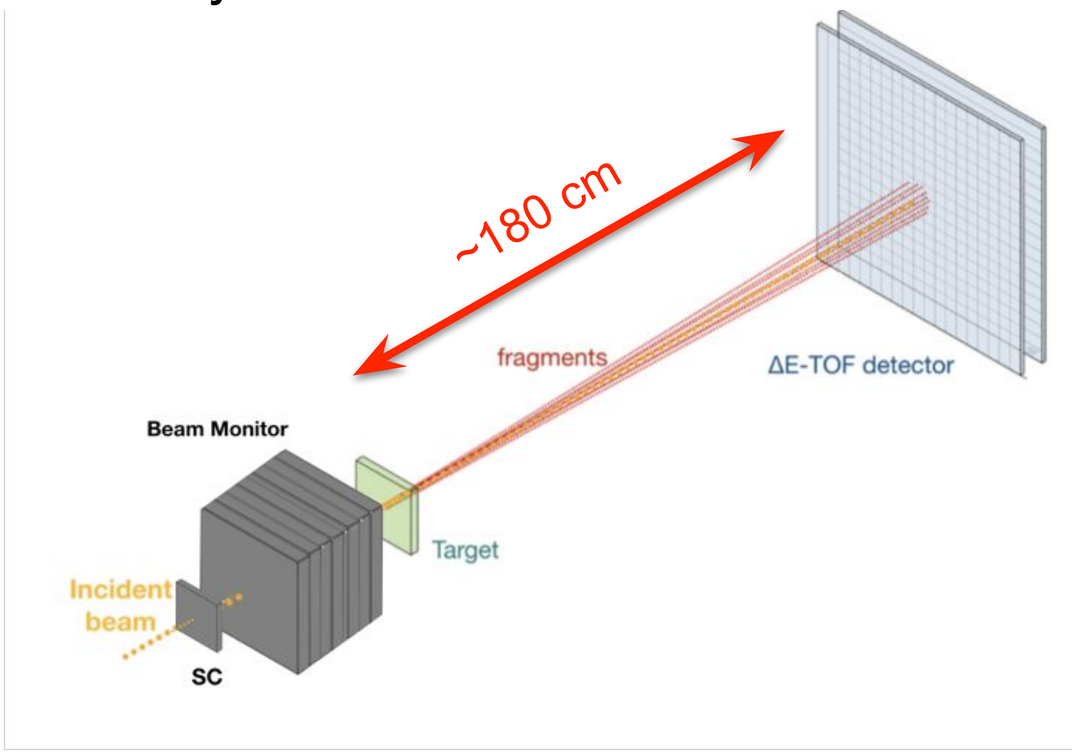
FOOT experimental status

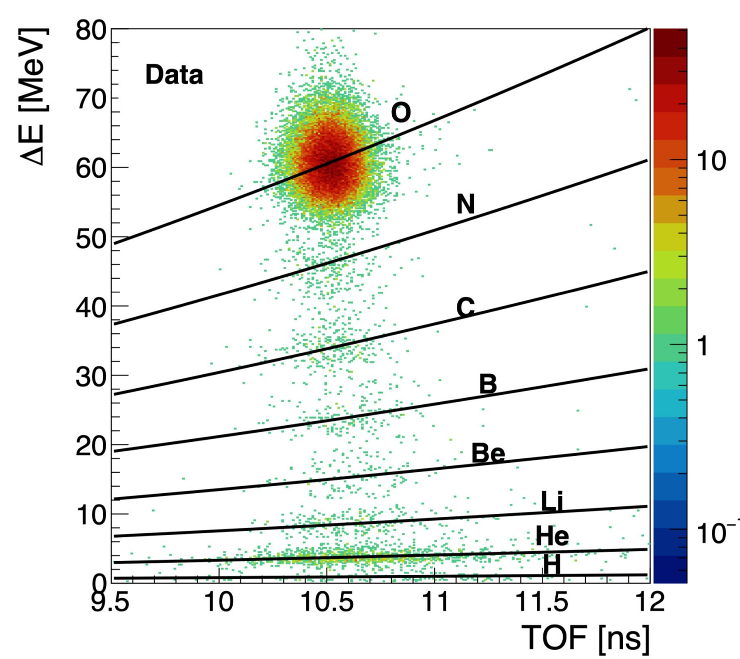
- Experiment under construction since 2019.. Current issue is the assembly of the permanent magnets → going for integrated cross sections
- First data taking @ GSI with SC, BM, target & TofWall
  - already able to measure some charge changing cross section for ^{16}O of 400 MeV/u on graphite!



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

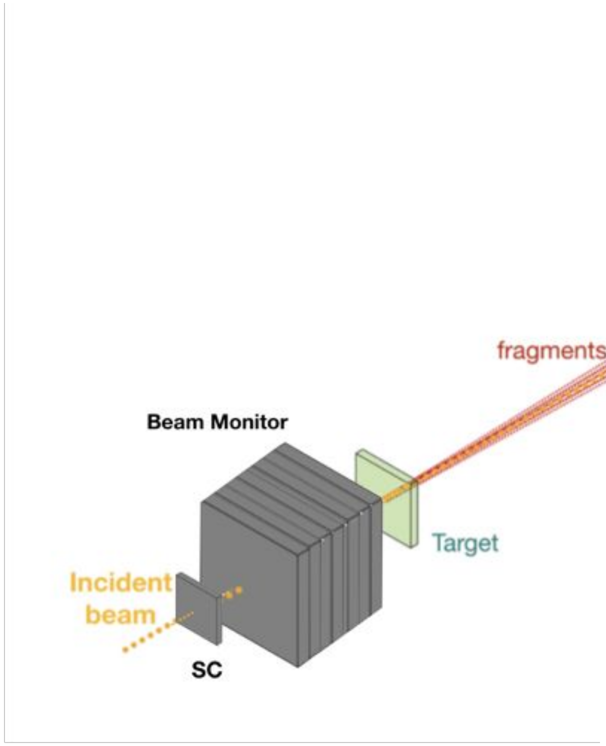
- Without magnets / trackers → Z id is performed by means of dE/dx vs time of flight measurements
  - Measurements precision limited by statistics: max rate of 1kHz due to ‘slow’ readout of TW + small target thickness to avoid re-fragmentation of ions inside the tgt… → small fragmentation yield





The background subtraction

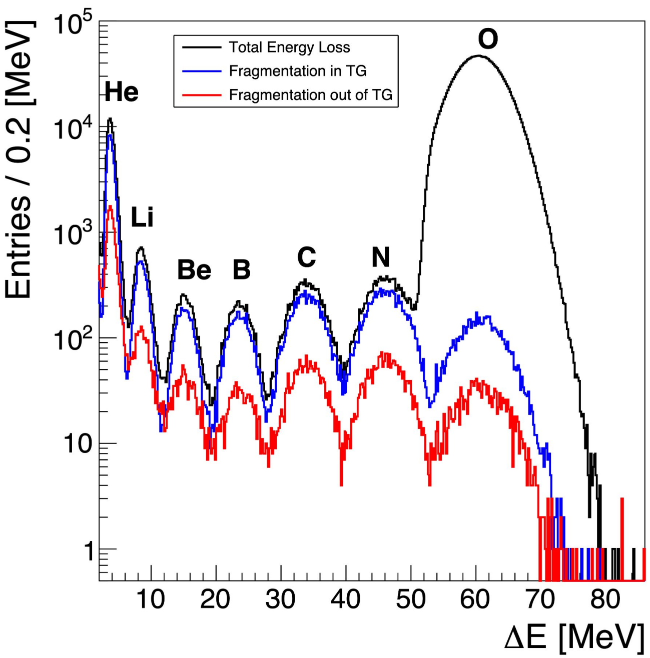
- The experiment is carried out 'in air' and care has to be taken in subtracting the 'out of target' fragmentation →calibrated on data, removing the target



Data

Element	$N_{\text{noTG}}(Z)$	$N_{\text{TG}}(Z)$
N_{prim}	61516	31660
He	445 ± 21	1006 ± 32
Li	85 ± 9	149 ± 12
Be	73 ± 8	75 ± 9
B	88 ± 9	136 ± 12
C	156 ± 12	231 ± 15
N	207 ± 14	248 ± 16

MC simulation



σ(Z) measurements

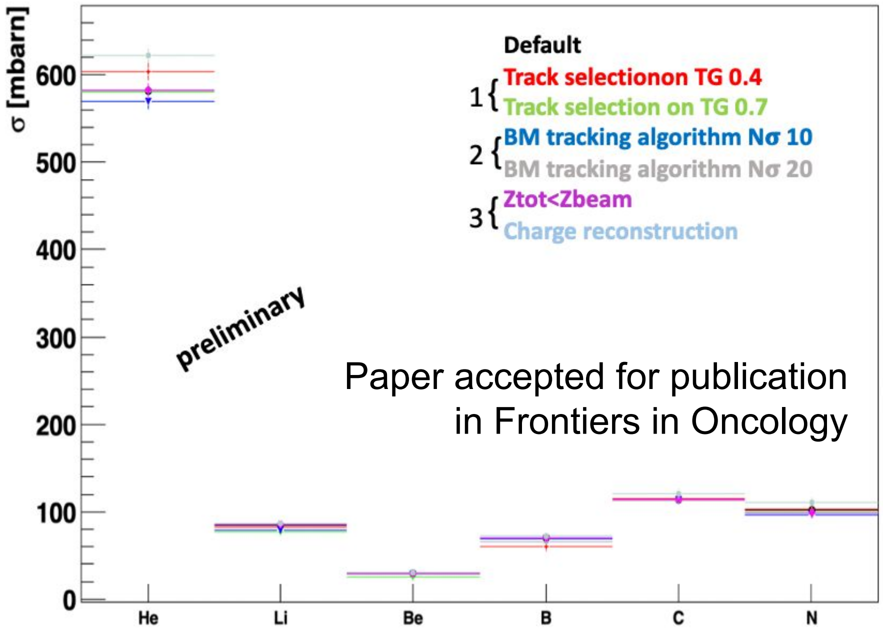
$$\sigma(Z) = \int_{E_{\min}}^{E_{\max}} \int_0^{\Delta\theta} \left(\frac{\partial^2\sigma}{\partial\theta\partial E_{\text{kin}}}\right) d\theta dE_{\text{kin}} = \frac{N_{\text{frag}}(Z)}{N_{\text{prim}} \cdot N_{\text{TG}} \cdot \varepsilon(Z)}$$

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

ε(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)

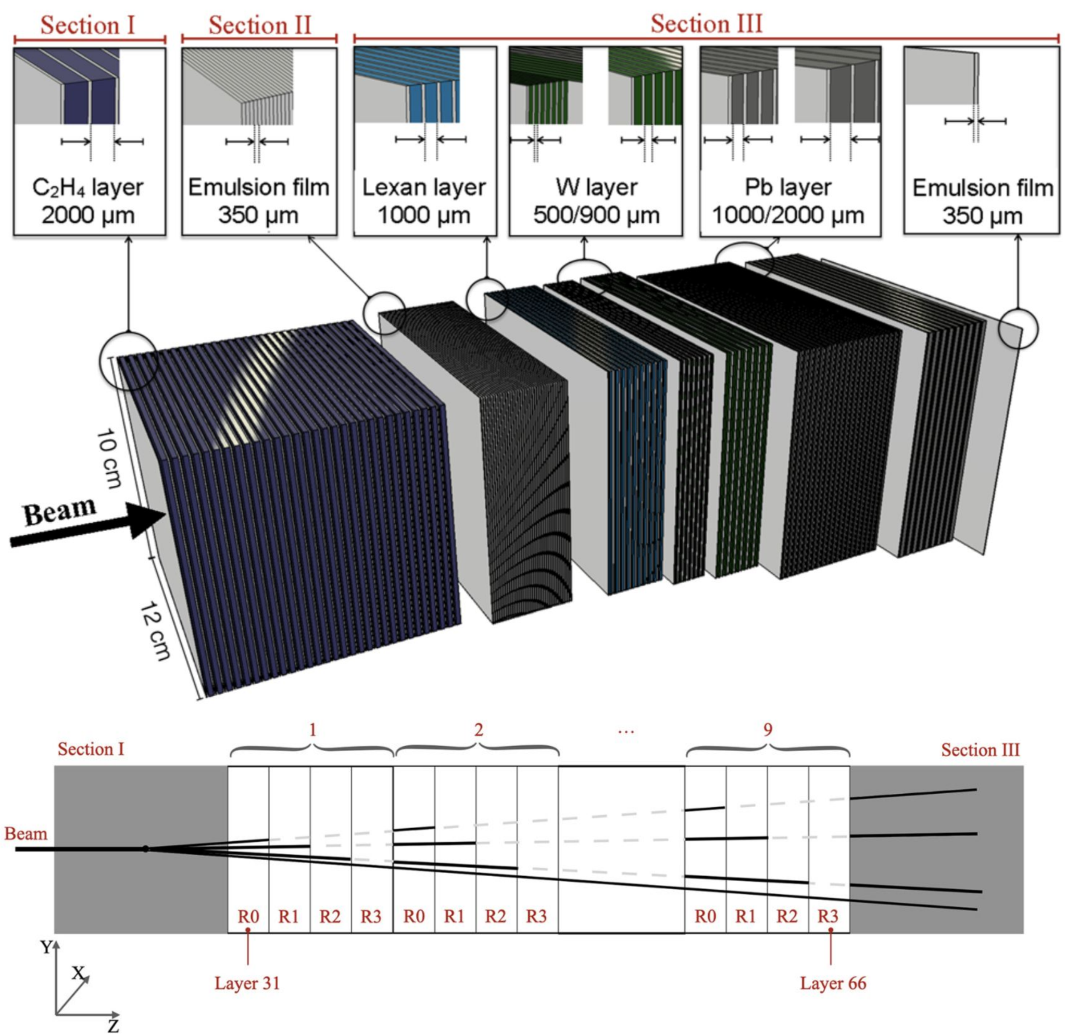
Element	$\sigma_{frag} \pm \Delta_{stat} \pm \Delta_{sys} [mbarn]$	$\Delta_{stat}/\sigma_{frag}$	$\Delta_{sys}/\sigma_{frag}$	$\sigma_{MC} [mbarn]$
He	$625 \pm 22 \pm 21$	3.6%	3.6%	621
Li	$85 \pm 10 \pm 5$	11.9%	5.6%	67
Be	$31 \pm 10 \pm 3$	31.8%	8.8%	33
B	$70 \pm 10 \pm 5$	14.9%	7.3%	38
C	$113 \pm 12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



Paper accepted for publication in Frontiers in Oncology

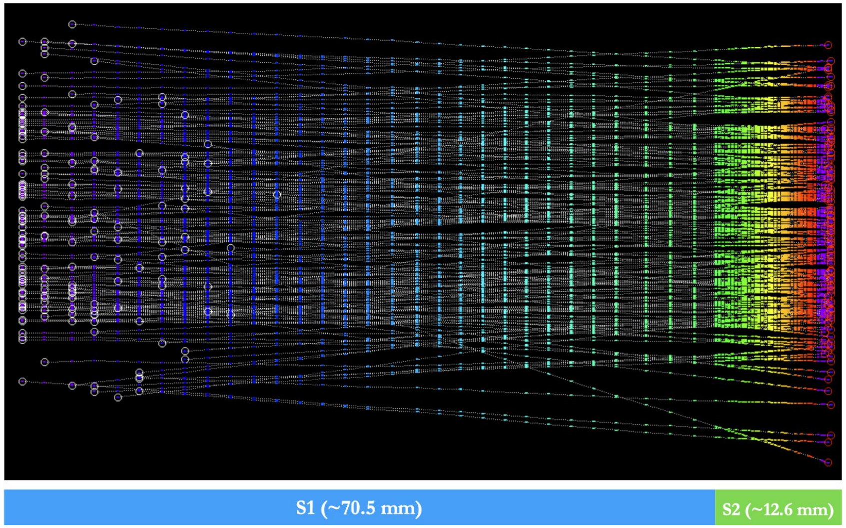
ECC a 'full' compact detector!

➡ To recover angular acceptance… Emulsion 'cloud' chambers!



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

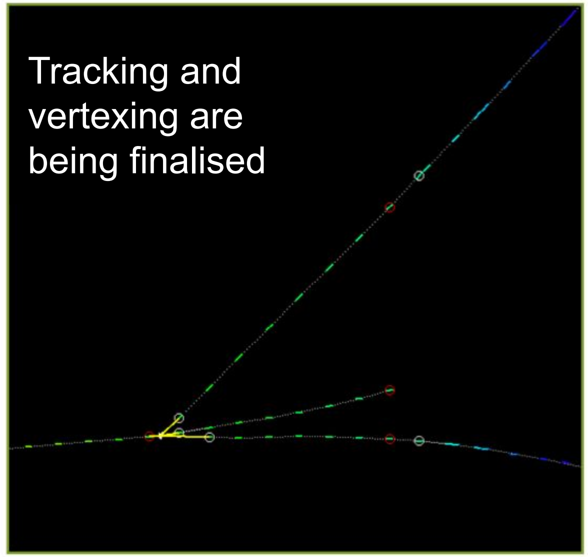
Matching tracks btw S1 & S2

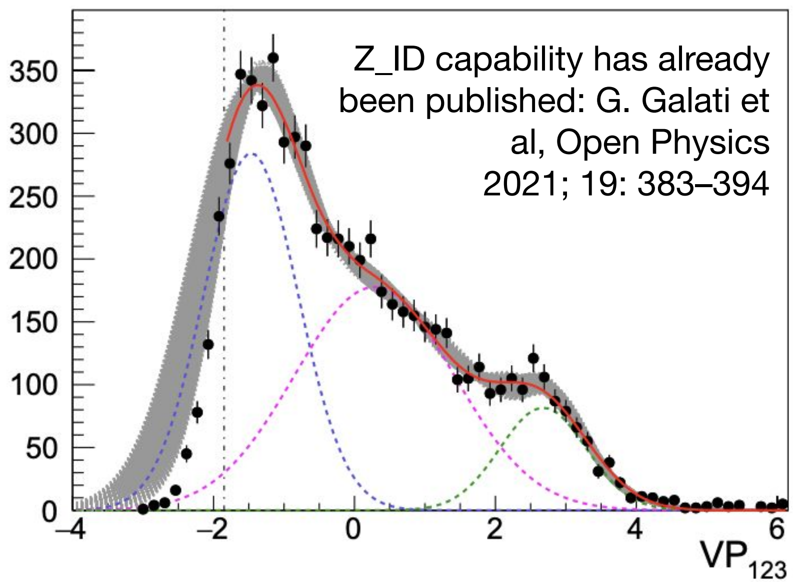


data from GSI 2019 data taking

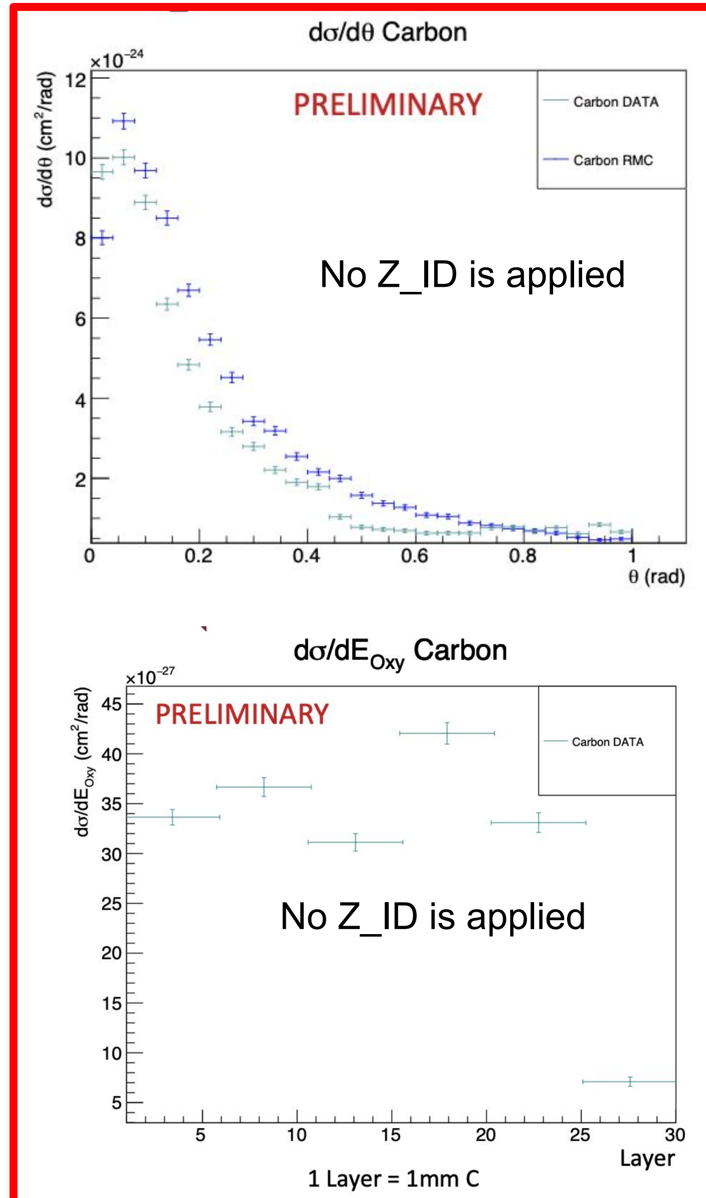
CS are behind the corner!

In 2019 four ECC (2 C, and 2 C_2H_4) were exposed to two different ^{16}O beams of 200 and 400 MeV/u kin energy



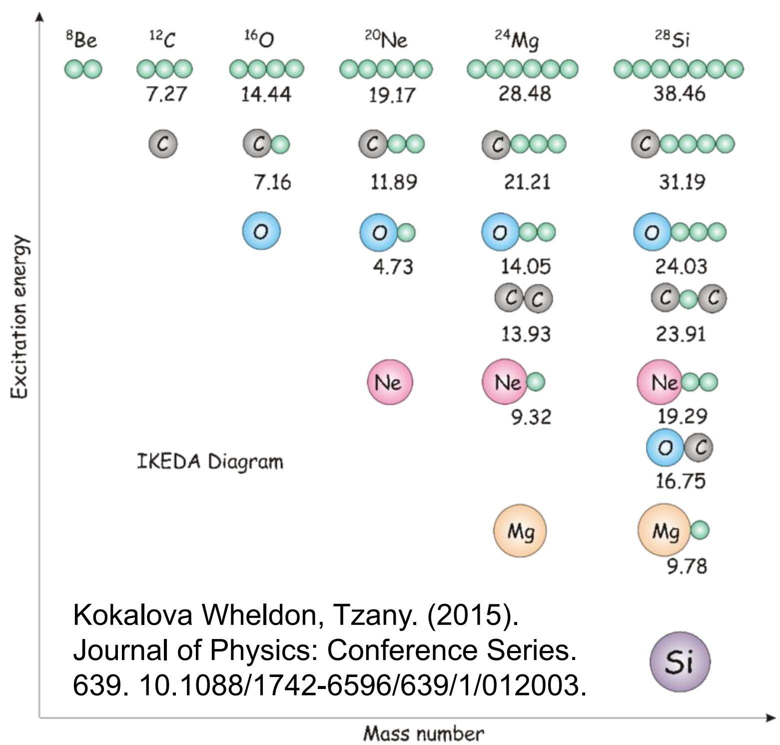


Total cross sections are already available!



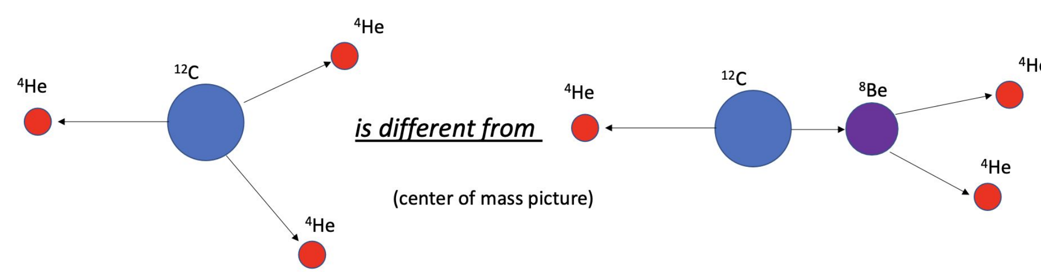
Nuclear clustering & α production

➡ 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



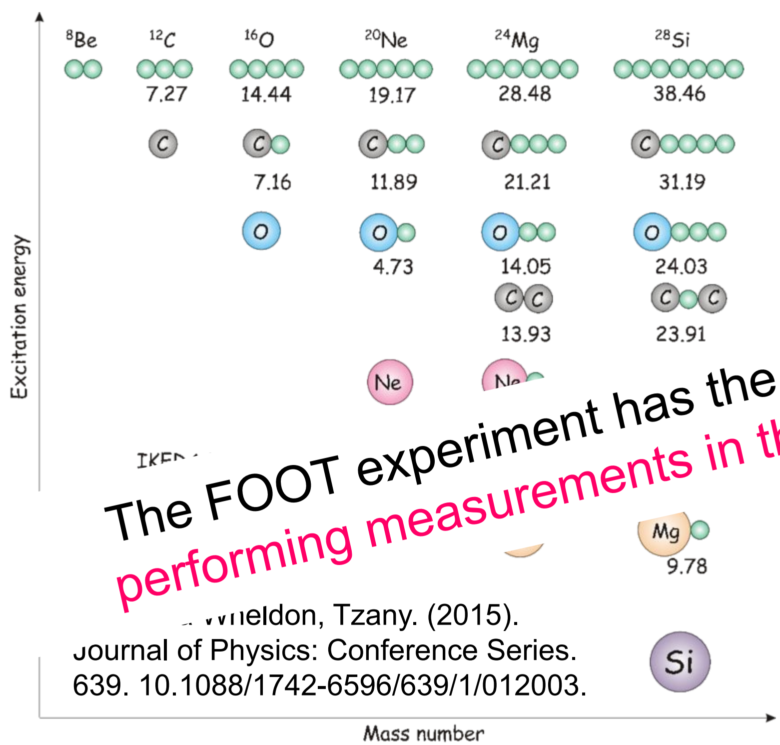
The existence of preferential fragmentation channels like $^{12}C \rightarrow 3\ ^{4}He$ and $^{16}O \rightarrow 4\ ^{4}He$ is well experimentally established, mainly for E/A > 1 GeV/nucleon

What happens @ energies relevant for PT & SRP? → crucial impact on PT as α have the highest LET, and most significant contribution to RBE



Nuclear clustering & α production

- 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



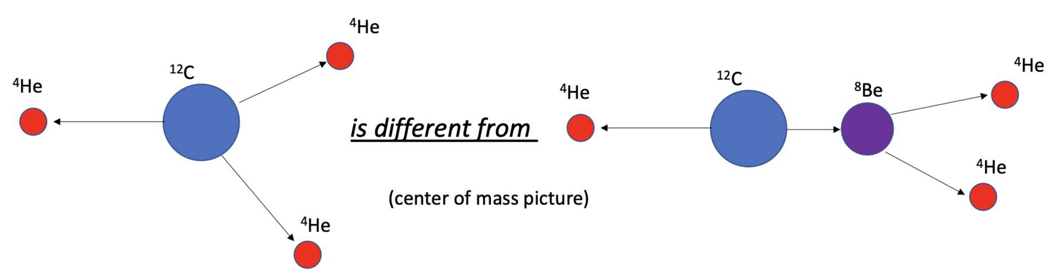
... Wheldon, Tzany. (2015). Journal of Physics: Conference Series. 639. 10.1088/1742-6596/639/1/012003.

The existence of preferential fragmentation channels like $^{12}C \rightarrow 3\ ^4He$ and $^{16}O \rightarrow 4\ ^4He$ is well experimentally establish...

for E/A > 1 GeV/...

...levant for PT & ...mpact on PT as α have the ...est LET, and most significant contribution to RBE

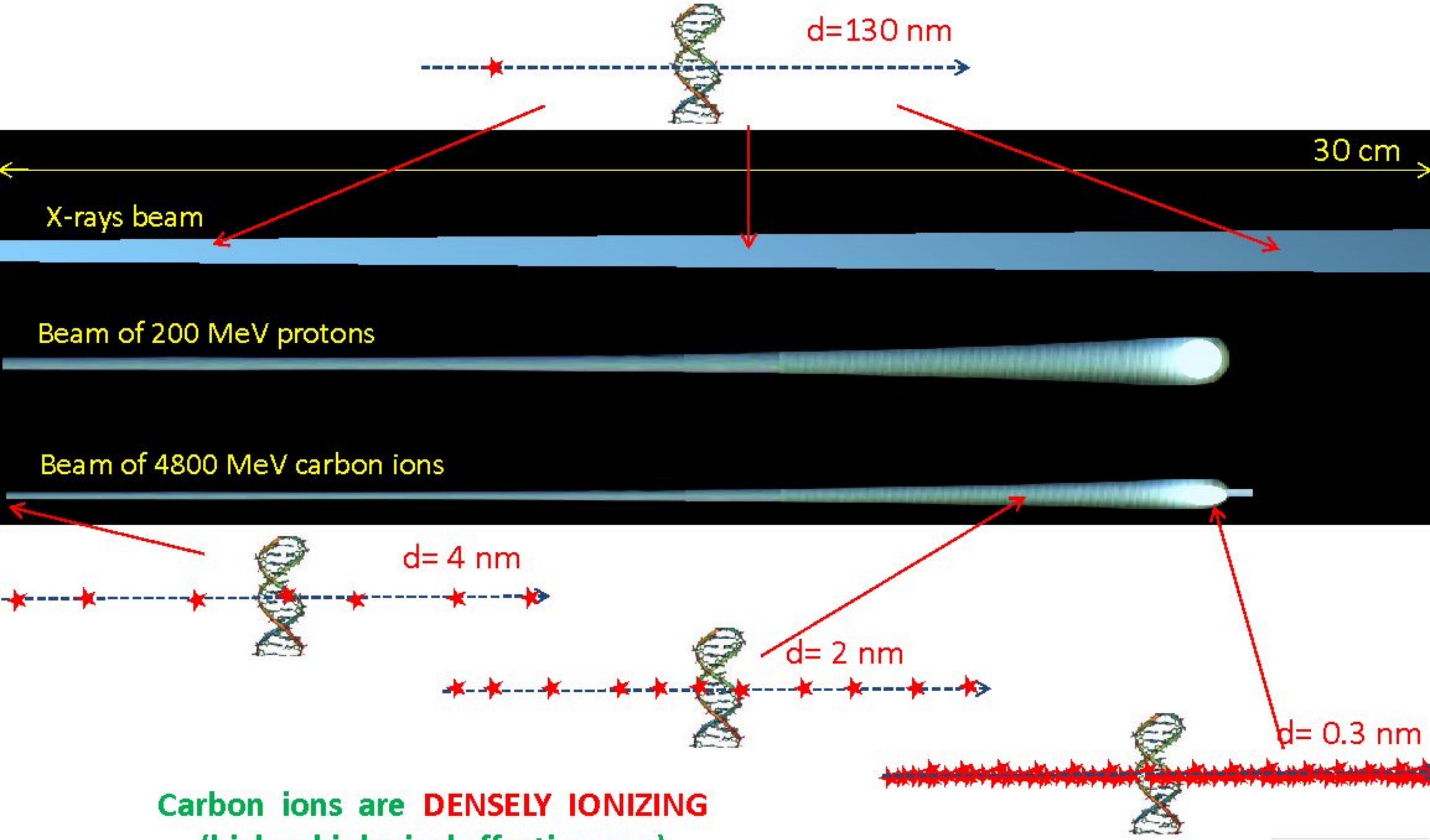
The FOOT experiment has the huge opportunity of studying such effect, performing measurements in the energy range btw 100 and 1000 MeV/u



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)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Courtesy U.Amaldi

TERA

"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

⇩

γ 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}He	100, 180	C, Al, Cu, Pb	
^{12}C	100, 180,400	C, Al, Cu, Pb	
^{20}Ne	100, 180,400	C, Al, Cu, Pb	
^{28}Si	800	C, Al, Cu, Pb	HIMAC by Kurosawa et al.
^{40}Ar	400	C, Al, Cu, Pb	
^{56}Fe	400	C, Al, Cu, Pb	
^{126}Xe	400	C, Al, Cu, Pb	
^{20}Ne	337	C, A, Cu and U	BEVALAC by Schimmerling et al.
^{93}Nb	272	Al, Nb	BEVALAC by Heilbronn et al.
^{93}Nb	435	Nb	
^{4}He	155	Al	NSRL by Heilbronn et al.
^{12}C	155	Nb	
^{4}He	160	Pb	SREL by Cecil
^{4}He	180	C, H_2O, steel, Pb	
^{12}C	200	H_2O	GSI by Günzert-Marx et al.
^{12}C	400	H_2O	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}He	135	C, Poly, Al, Cu, Pb	
^{12}C	135	C, Poly, Al, Cu, Pb	RIKEN by Sato et al.
^{20}Ne	135	C, Poly, Al, Cu, Pb	
^{40}Ar	95	C, Poly, Al, Cu, Pb	
^{12}C	290, 400	C, Cu, Pb	
^{20}Ne	400, 600	C, Cu, Pb	HIMAC Iwata et al.
^{40}Ar	400, 560	C, Cu, Pb	
^{4}He	230	Li, C, CH_2, Al, Cu, Pb	
^{14}N	400	Li, C, CH_2, Al, Cu, Pb	
^{28}Si	600	Li, C, CH_2, Al, Cu, Pb	HIMAC H ... al.
^{56}Fe	500	Li, C, CH_2, Al, Cu, Pb	
^{86}Kr	400	Li, C, CH_2, Al, Cu, Pb	
^{126}Xe	400	Li, C, CH_2, Al, Cu, Pb	

Tentative & incomplete list

Courtesy of M. Durante

only with detectors at 0°!

Available DDCS

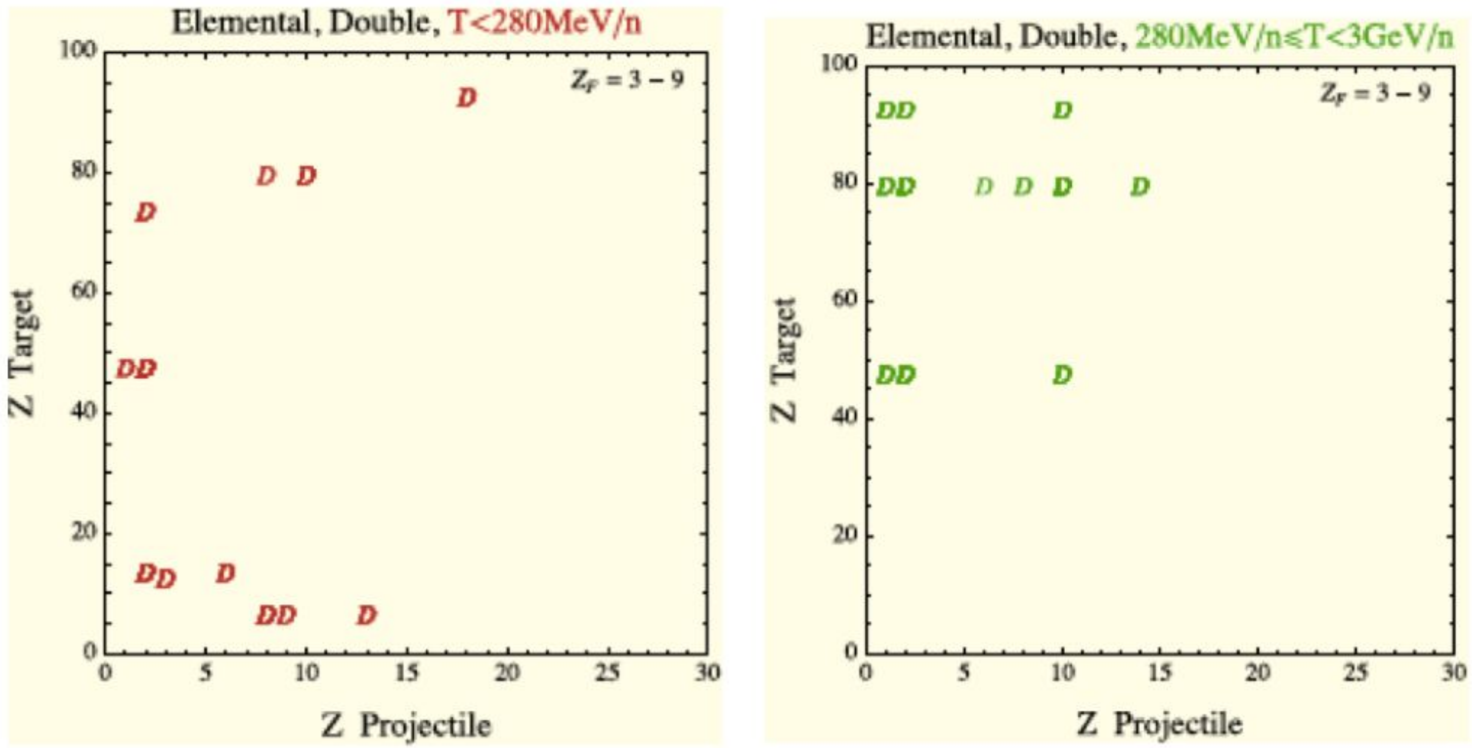
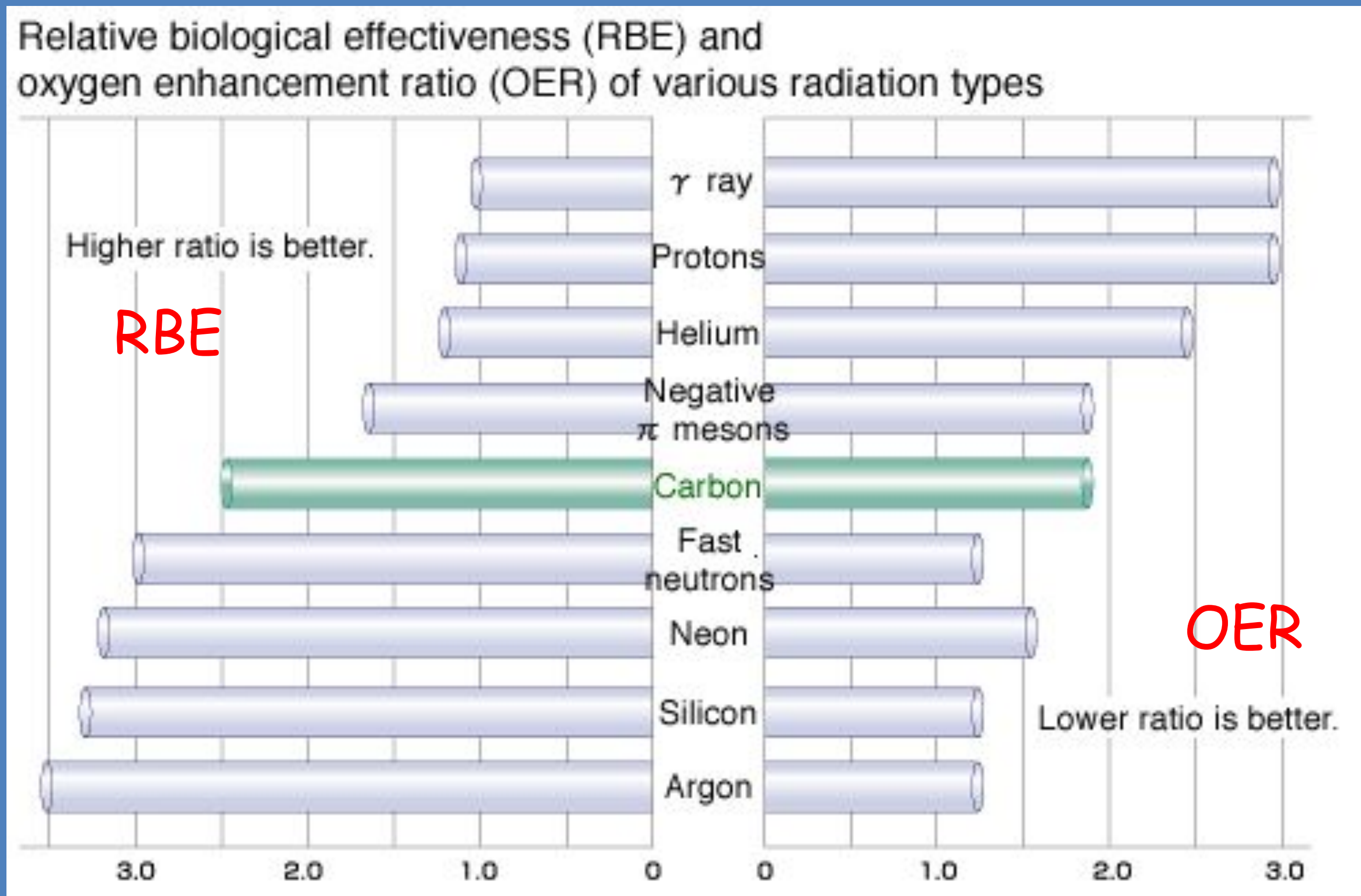


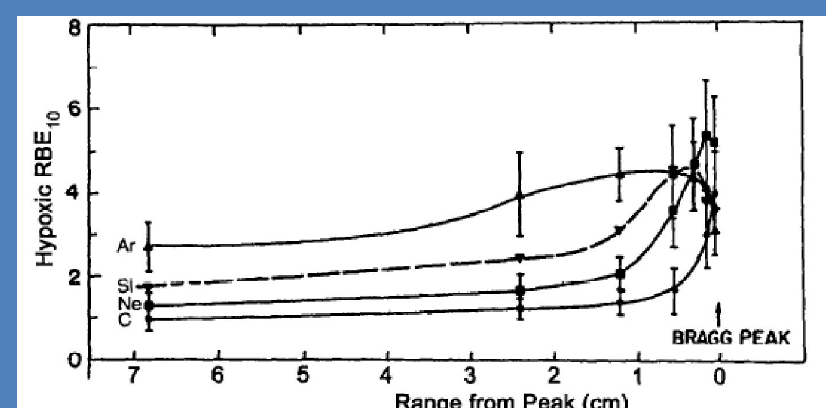
Figure 8 – Double differential cross sections available from literature for the production of medium-light fragments ($Z_F = 3-9$). The data are shown as function of projectile and target charge Z and divided into two projectile energy ranges (below 290 MeV/u and between 290 MeV/u and 3 GeV/u).

Radiations vs Biological effects



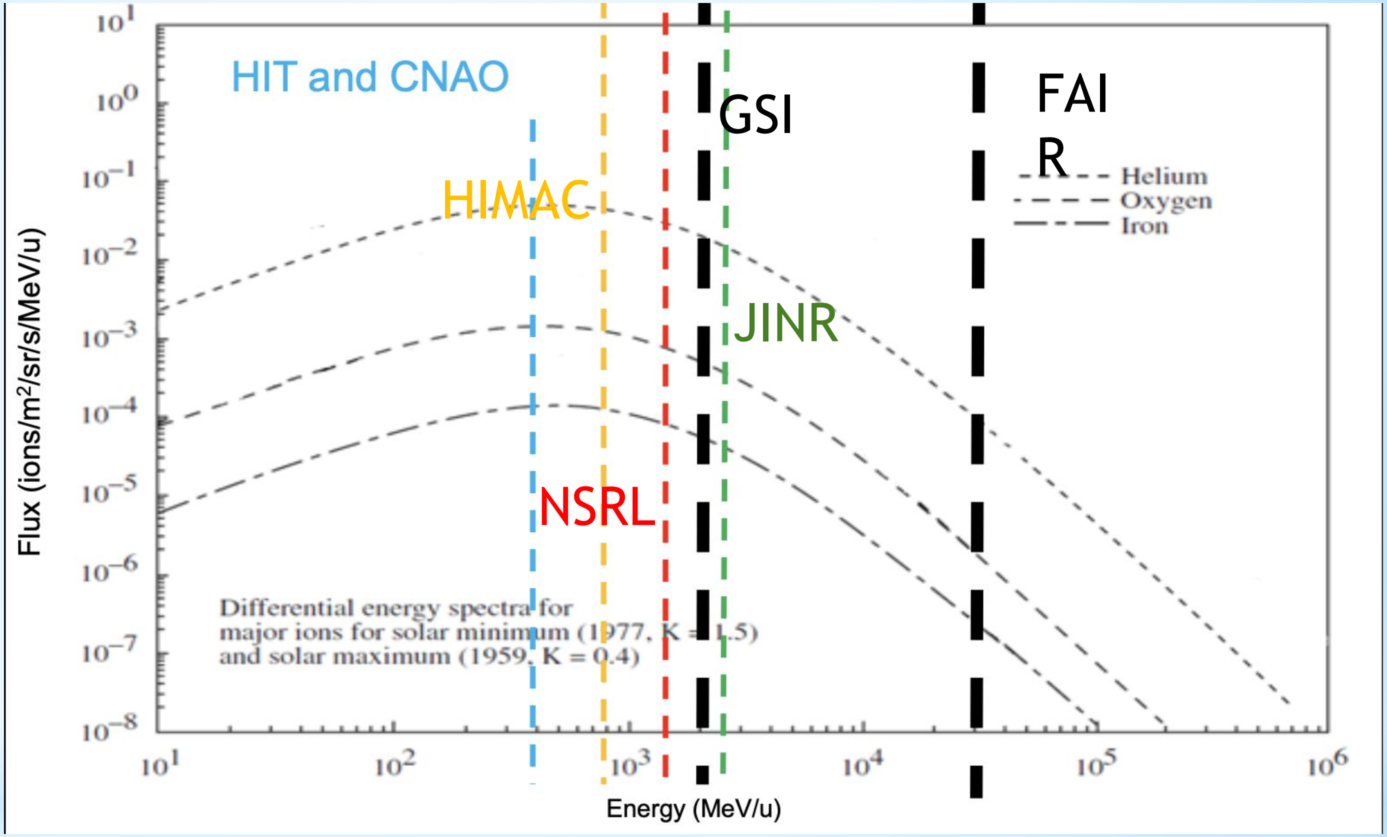
^{12}C -> good compromise between RBE and OER.

Optimal RBE profile vs penetration depth position.



On Earth exp: where and what?

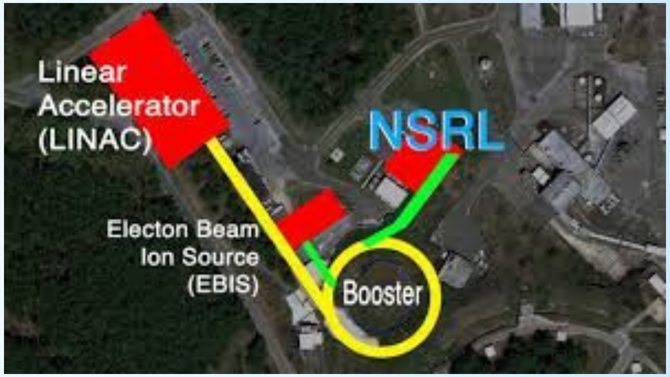
- ✔ Dose attenuation experiment behind shielding materials
- ✔ Fragmentation cross sections, measurement, if possible double differential

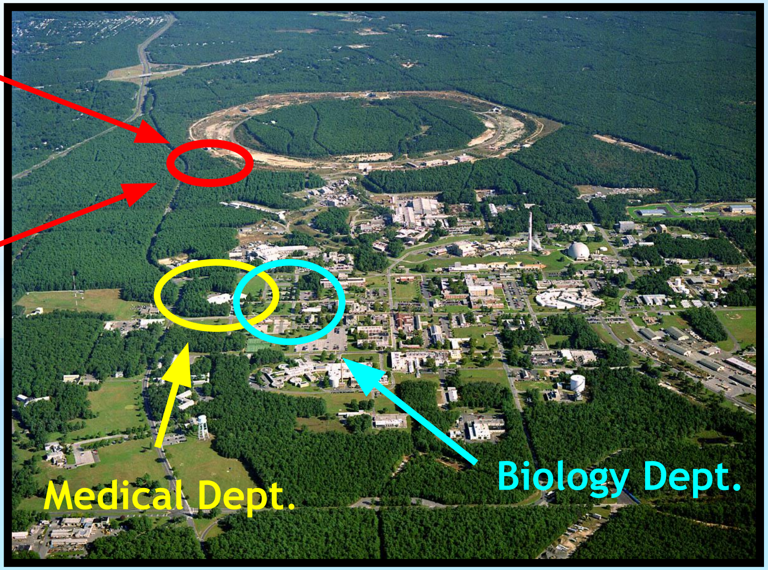


Few facilities provides the needed beam to explore GCR. Some are particle therapy treatment center: therapeutic beams have ~ same energy and ions of GCR!!!

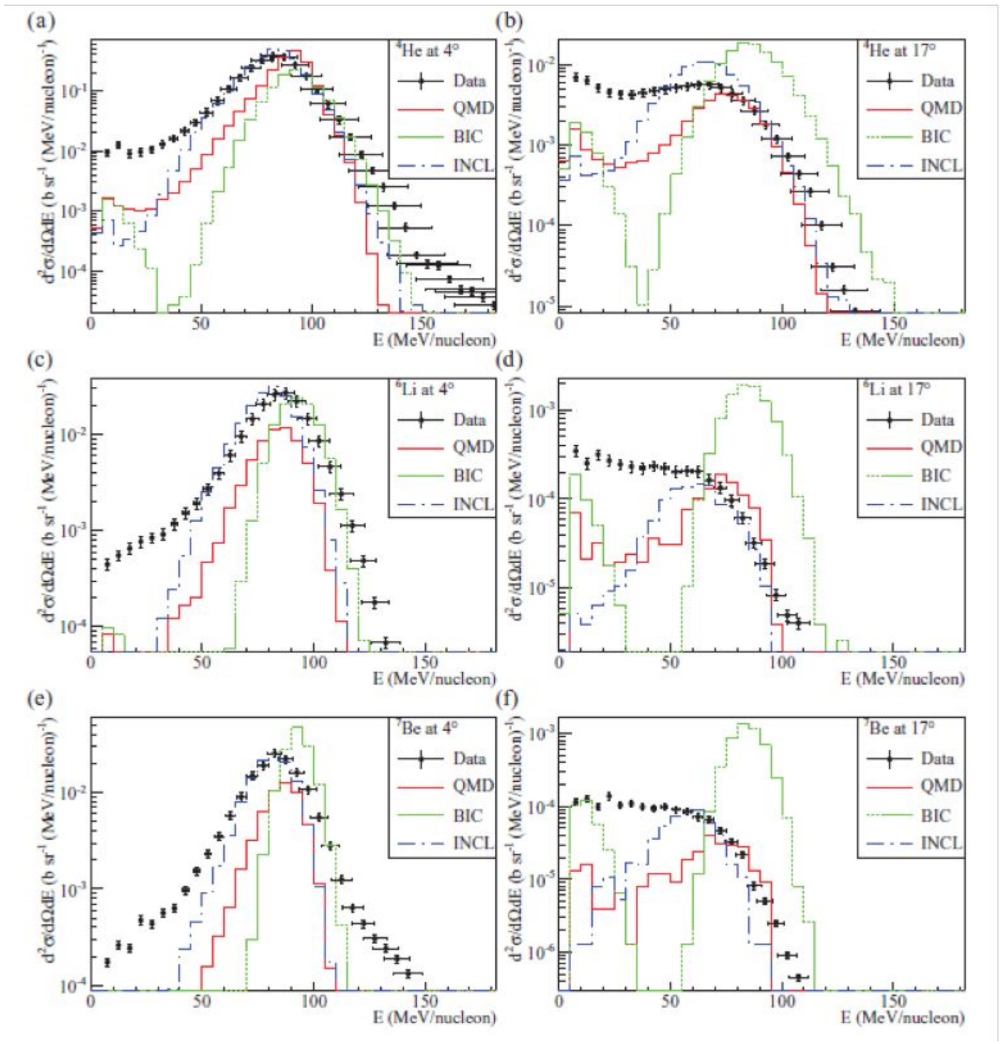
NASA Research Programs @BNL

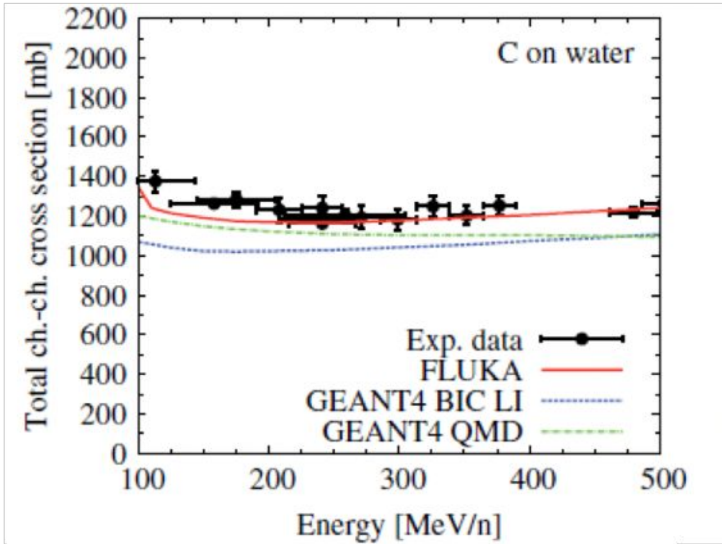
NASA Space Radiation Health Program at the Brookhaven National Laboratory, Upton, NY

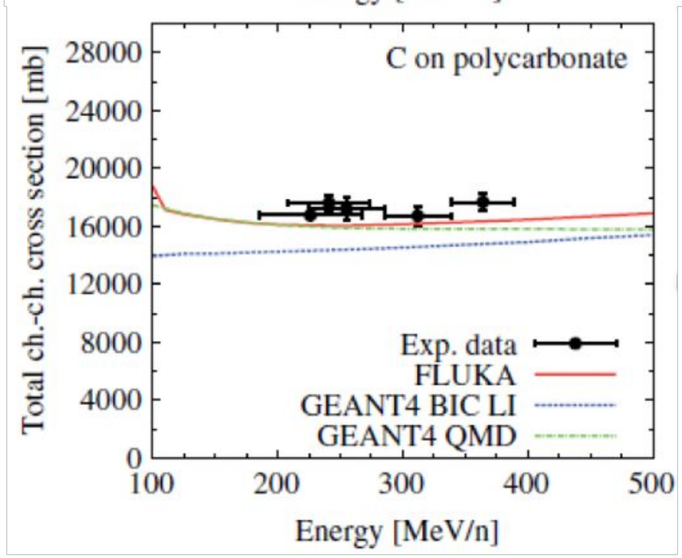




DDCS data - MC agreement







The challenge(s)

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

12C ions on thin Au target..