Nuclear data for nuclear medicine, hadrontherapy and space radiation protection

N. Arbor, P. Dessagne, Ch. Finck, A. Guertin, F. Haddad, G. Henning, S. Higueret, D. Husson, M. Kerveno, C. Koumeir, M. Labalme, X. Ledoux, F. Poirier, S. Salvador, T. Sounalet, M. Vanstalle

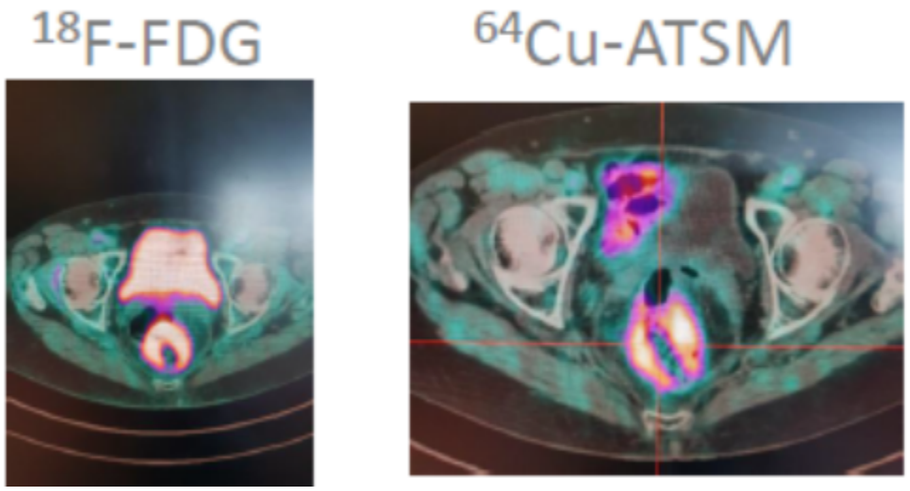
05/02/2020

Why do we need nuclear data for health?

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- Optimization of specific radionuclides production

Personalized medicine



Tumoral Hypoxia Mapping in colorectal cancer with ^{64}Cu-ATSM

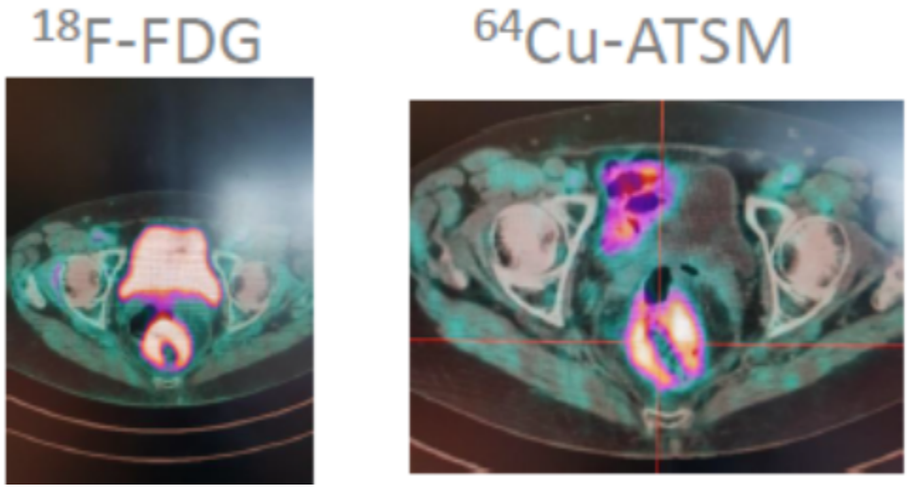
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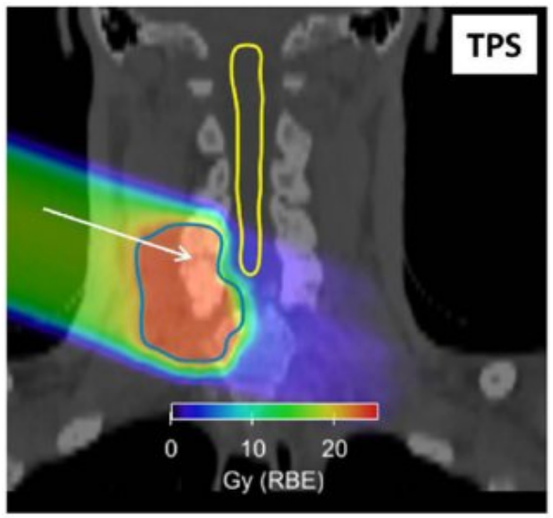
Personalized medicine

- Nuclear reactions of incident ion beam with target responsible of additional dose after the Bragg peak

Hadrontherapy



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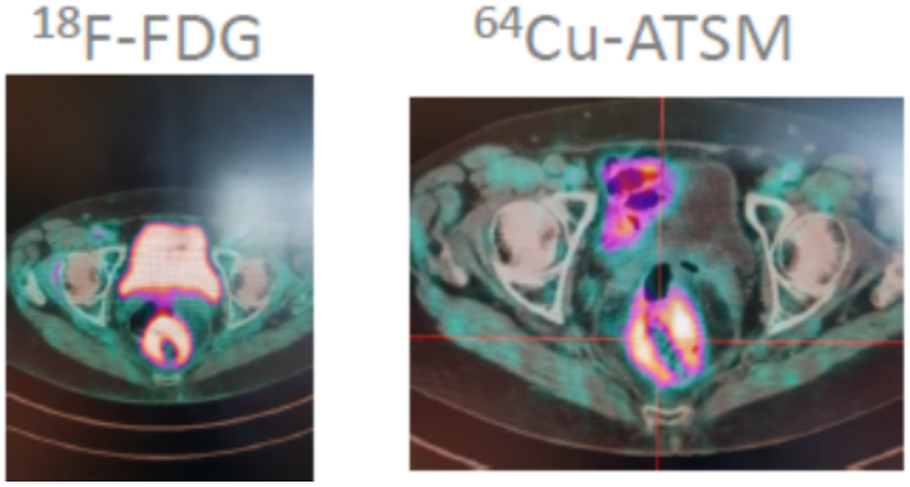
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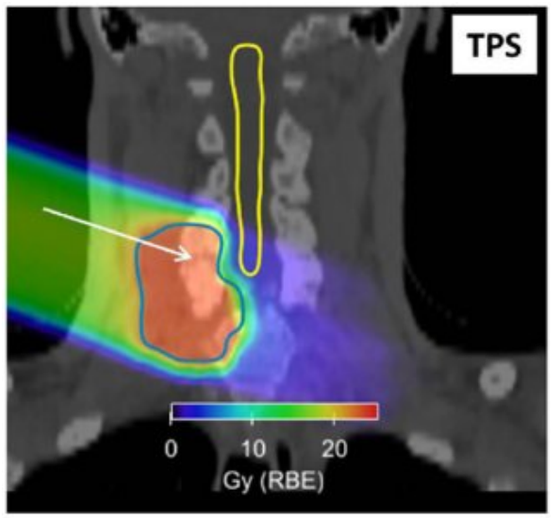
Hadrontherapy

- GCR (Galactic Cosmic Rays) = main hindrance for long-term exploratory missions in deep space

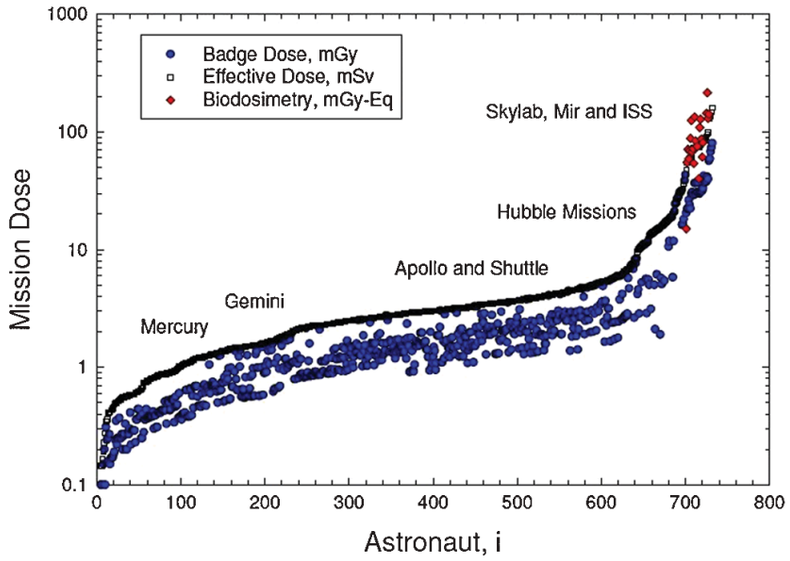
Space radiation protection



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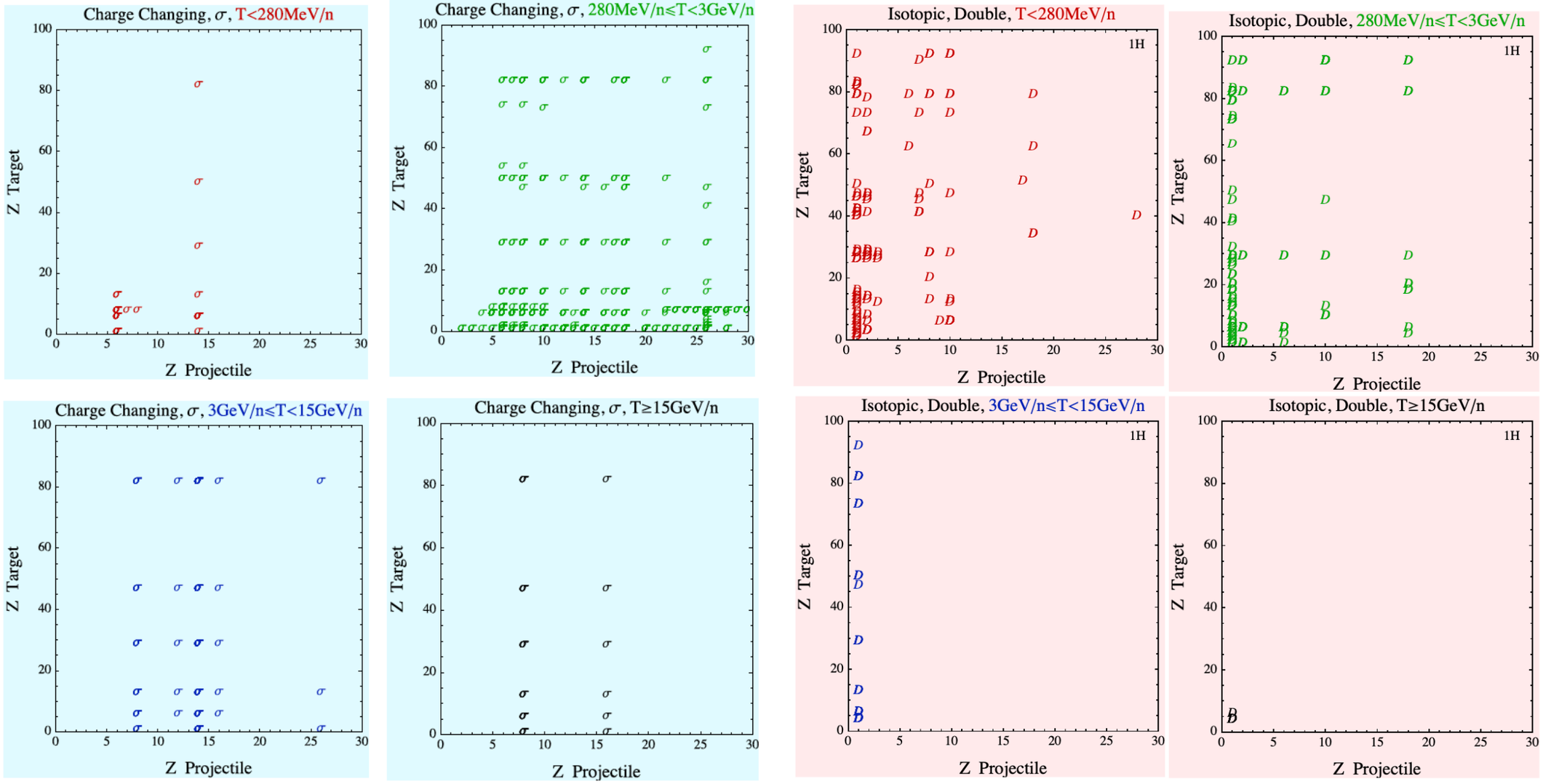
From **Battistoni et al.**, "*The FLUKA code: an accurate simulation tool for particle therapy*", Frontiers in Oncology (2016).



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

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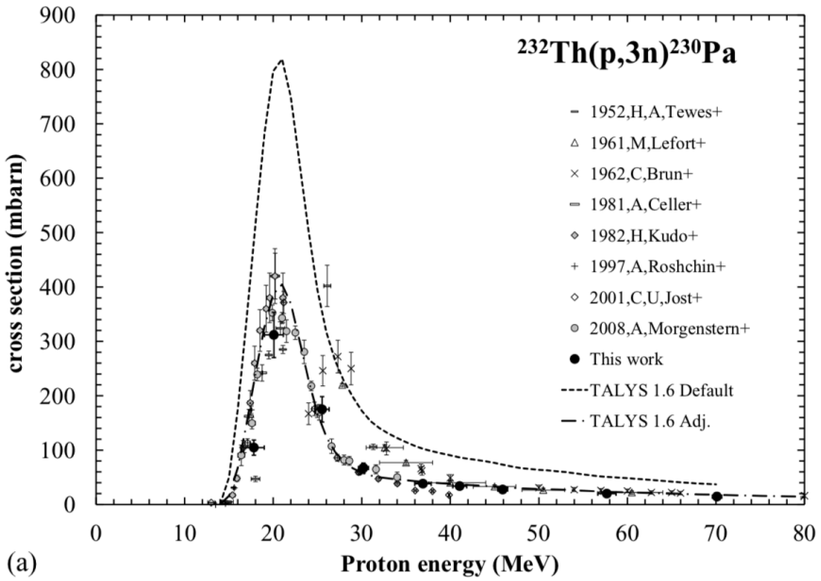
- Lack of experimental data at energies between 10 MeV/n and 10 GeV/n (energies of interest for **radioisotopes** production, **hadrontherapy** and **space** applications)



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

Why do we need nuclear data for health?

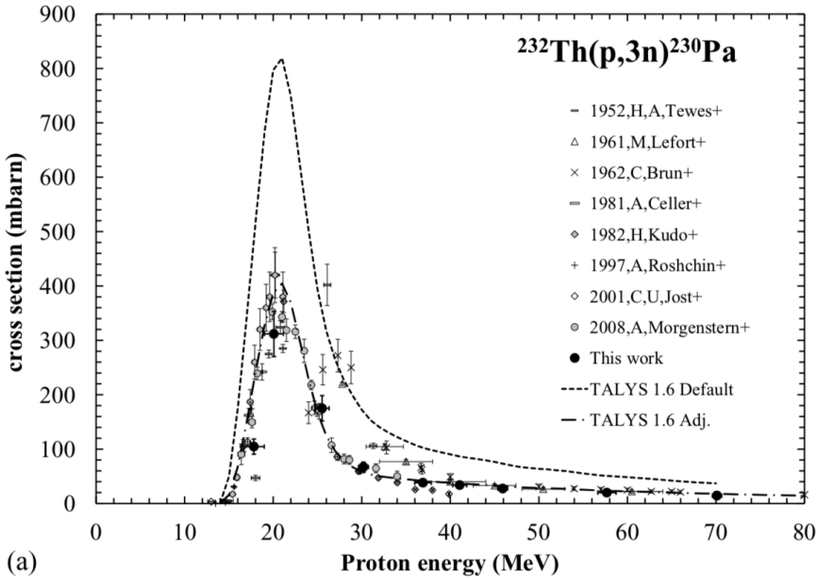
- **Discrepancies** between radiation transport models and existing measurements



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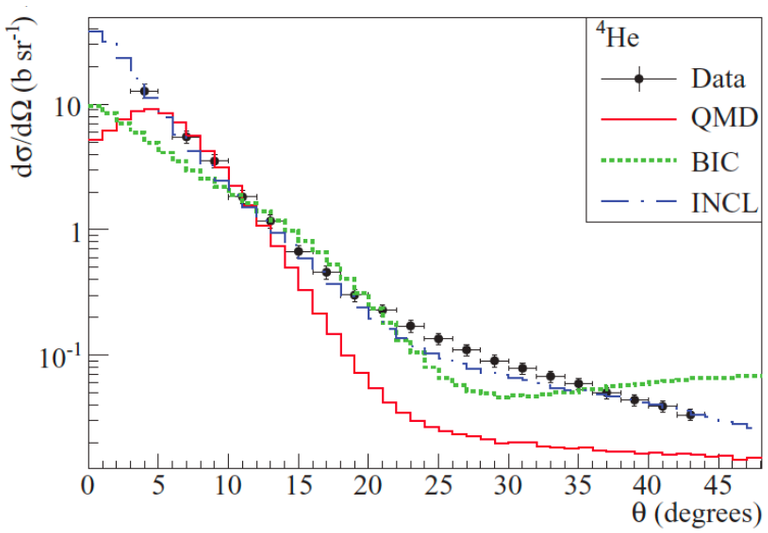
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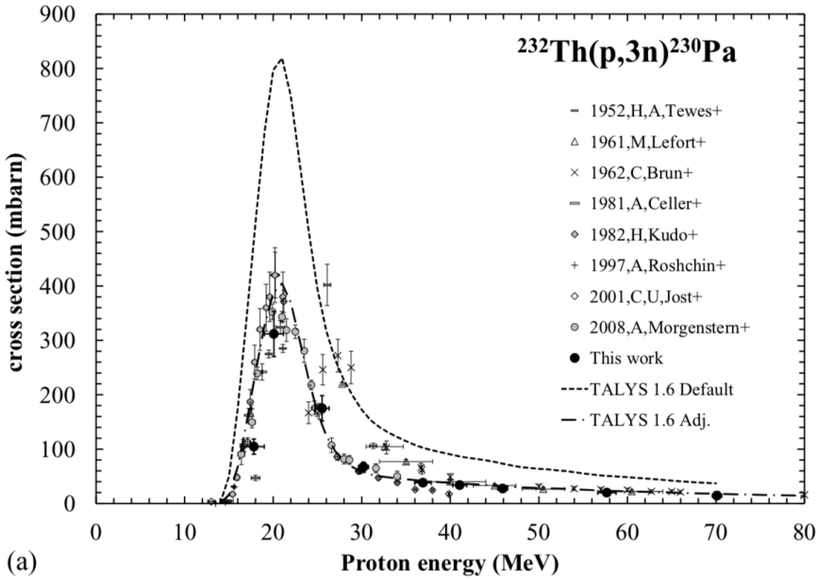
Differential angular cross-sections of $^{12}C(^{12}C,^{4}He)$ reaction @ 95 MeV/n



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

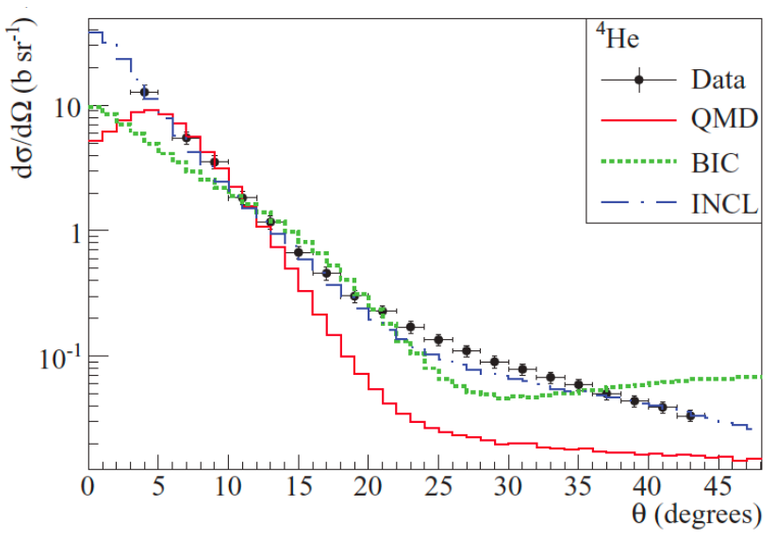
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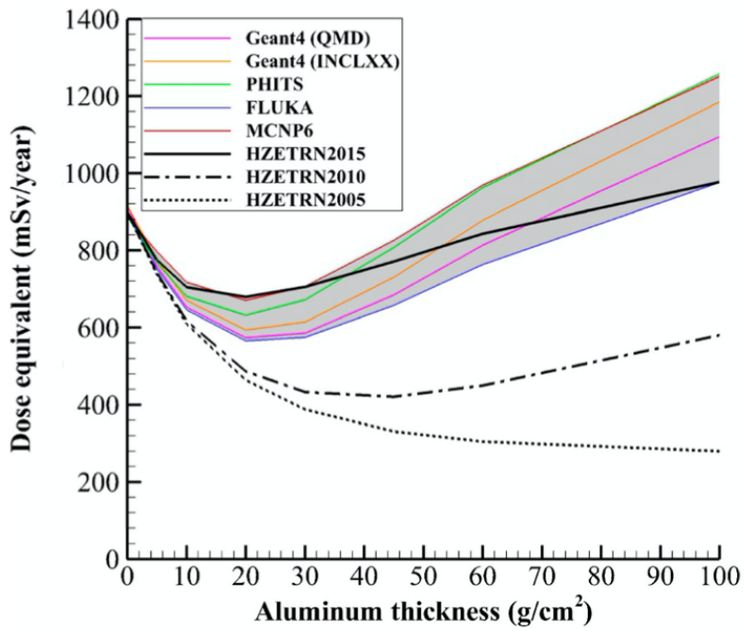


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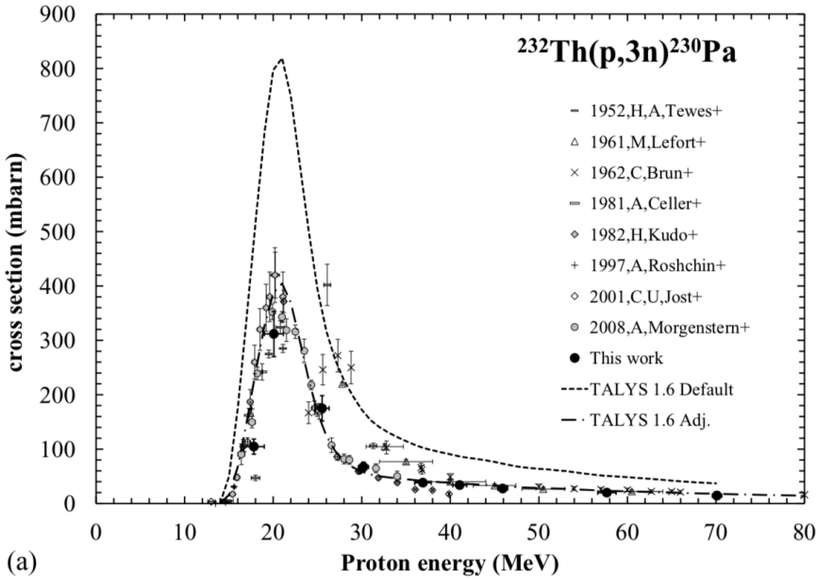
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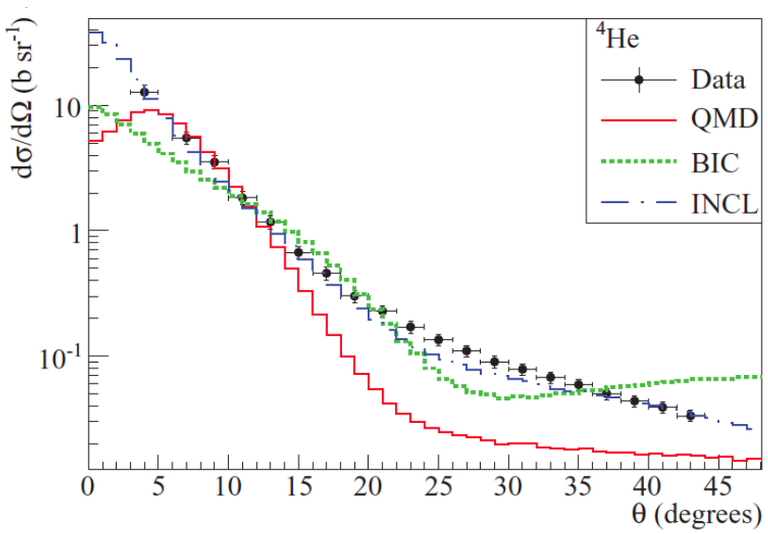
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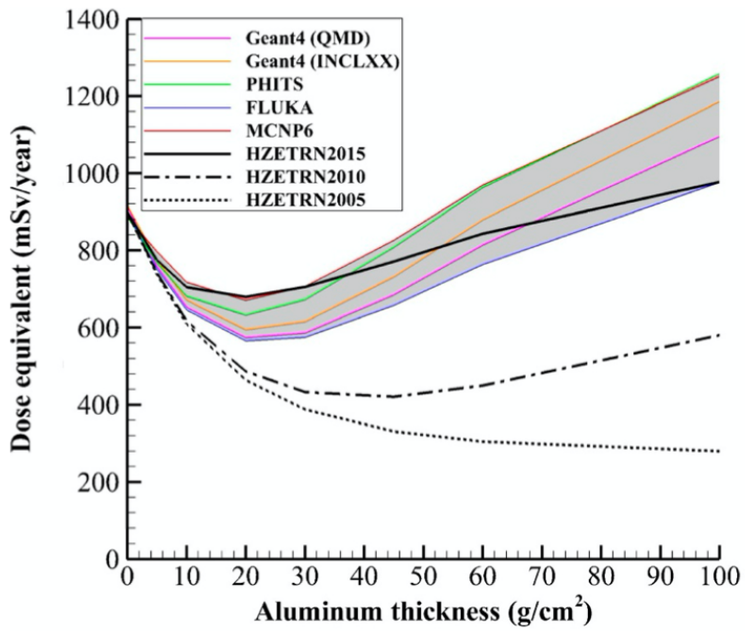


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- Necessity of **implementing data** in existing models or develop new ones

How and where measuring data?

- Existing facilities used for cross-sections measurements
  - ARRONAX (Nantes), p,d and α up to 70 MeV
  - GANIL (Caen), ions up to 95 MeV/n
  - GSI-SIS18 (Darmstadt, Germany), ions up to Z=92 and E=1 GeV/n
  - HIT (Heidelberg, Germany), p, ^{4}He, ^{12}C, ^{16}O up to 400 MeV/n
  - CNAO (Pavia, Italy), p or ^{12}C up to 400 MeV/n
  - MedAustron (Vienna, Austria), p up to 800 MeV, ^{12}C up to 400 MeV/n

— Cyclotron
— Synchrotron
— LINAC



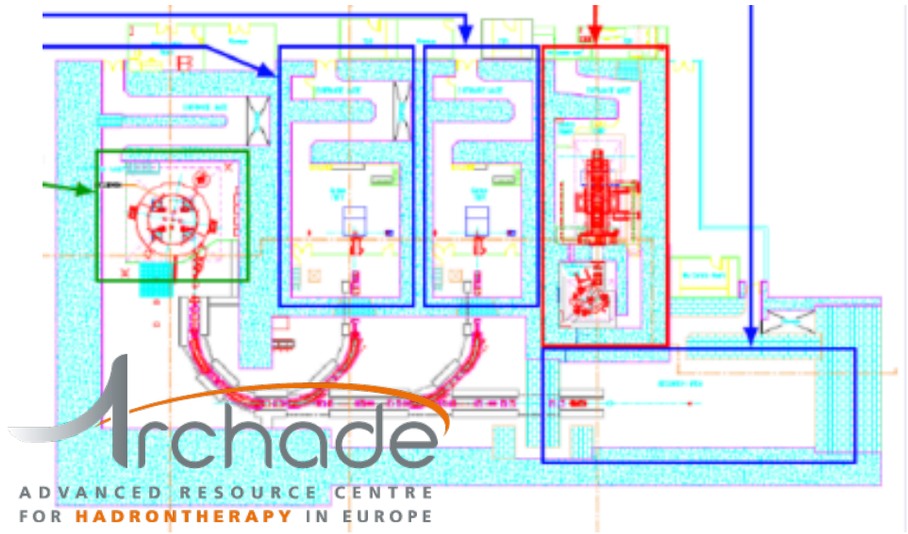
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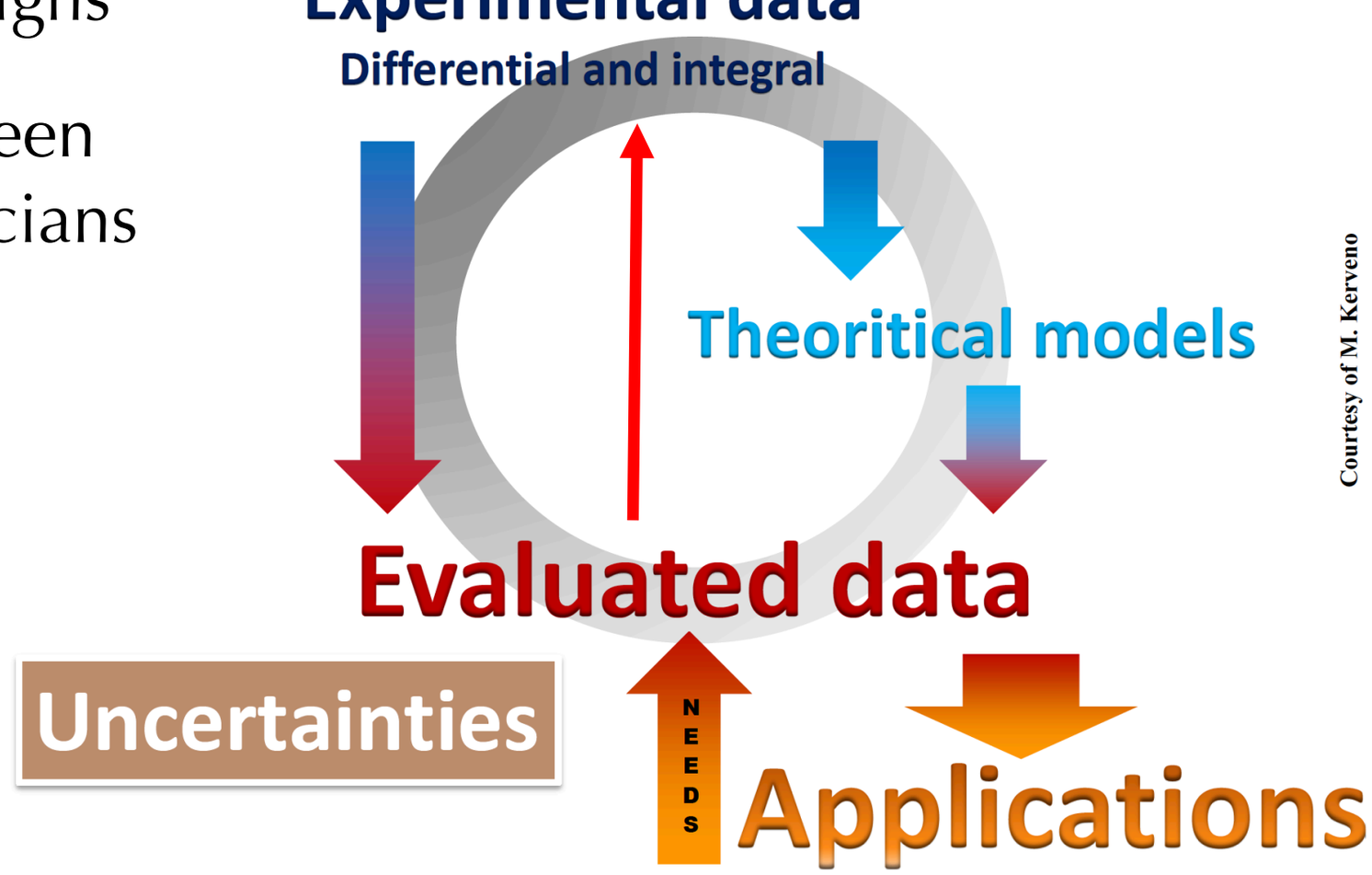
- New facilities will open access to wider energy ranges
  - SPIRAL2 (Caen), up to 33 MeV for p and <14.5 MeV/n for heavy ions + NFS, neutrons from 0.5 to 40 MeV
  - ARCHADE (Caen), ^{12}C up to 400 MeV/n ~ 2025
  - FAIR (Darmstadt, Germany), up to 10 GeV/n ~ 2025





Coordination of activities

- Nuclear energy applications as gold standard?
- **Promote** and **disseminate** all the data already acquired, through internationally available **database** and **publication**.
- Define the **needs** to prepare the next experimental campaigns
- Strengthen the **links** between experimentalists, theoreticians and evaluators



Courtesy of M. Kerveno

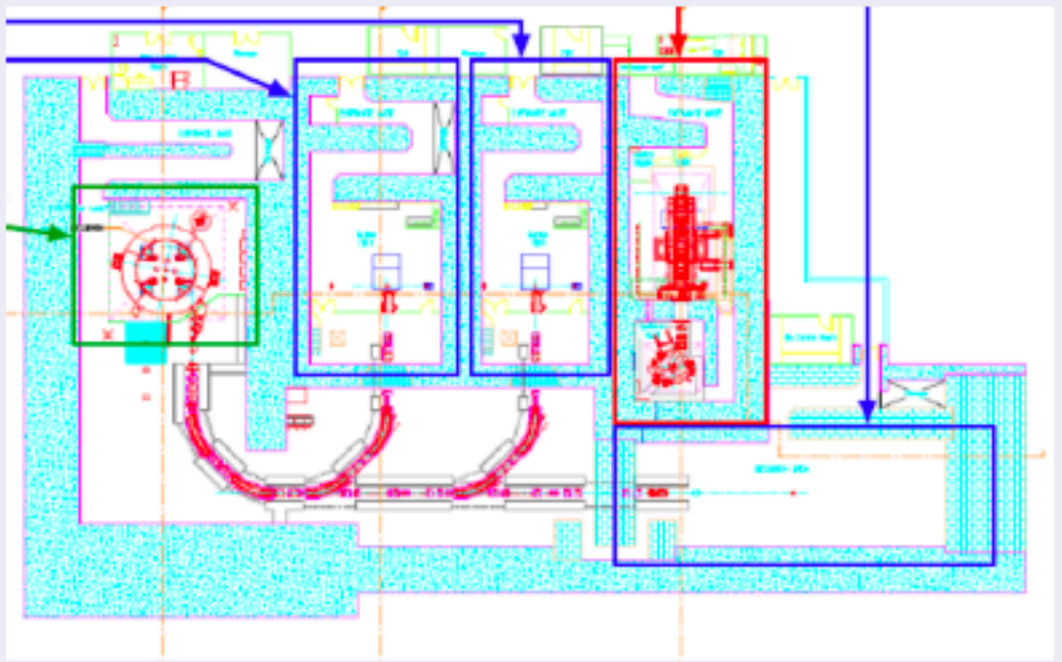
Radioisotopes

- Measurements of terbium isotopes:
  - ^{161}Tb from d+^{160}Gd reaction
  - ^{149}Tb, ^{152}Tb and ^{155}Tb from p + enriched Gd reaction
- Alpha-induced reactions:
  - Residue cross-section measurements on Pb and Bi
- Fission reactions:
  - Fission cross-section of induced p and d on U target
- ^{64}Cu:
  - p or d on ^{64}Ni reactions

Hadrontherapy

Long term program of systematic measurements of nuclear reactions for hadrontherapy from 50 to 400 MeV/n

- **ARCHADE** (t_0 = December 2014)
  - New resource center for hadrontherapy in Caen
  - First patient treated with proton in july 2018
  - First carbon beam in ∼2025
- ∼6×15 m^2 experimental room (physics:∼300 h/year)

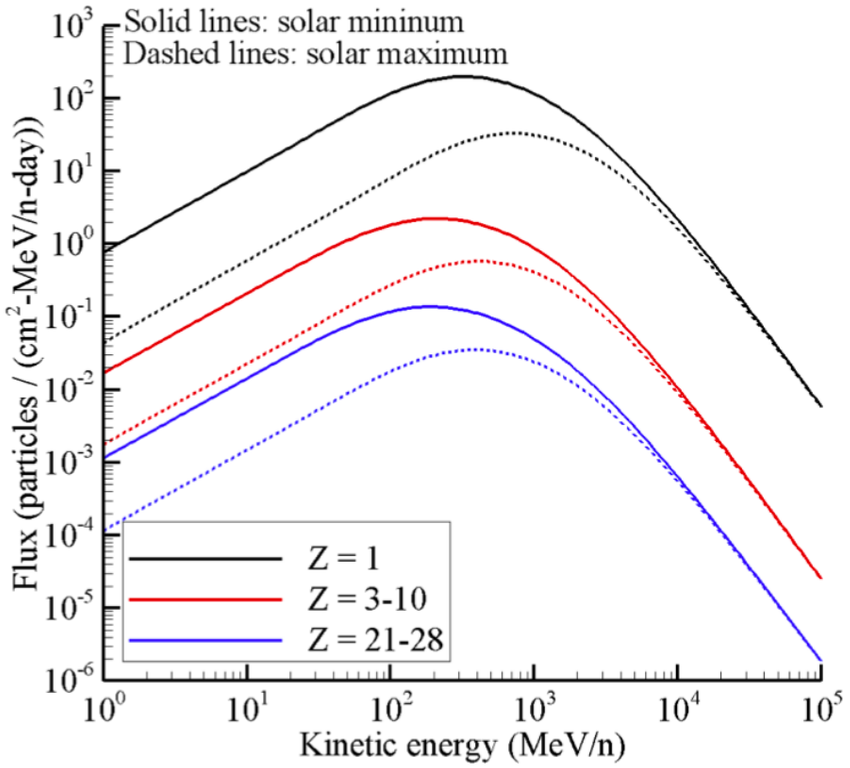


$\Rightarrow \frac{\delta^2\sigma}{\delta E \delta\Omega}$ measurements with α to ^{12}C (^{20}Ne) beams from 100 to 400 MeV/n.

Courtesy of M. Labalme

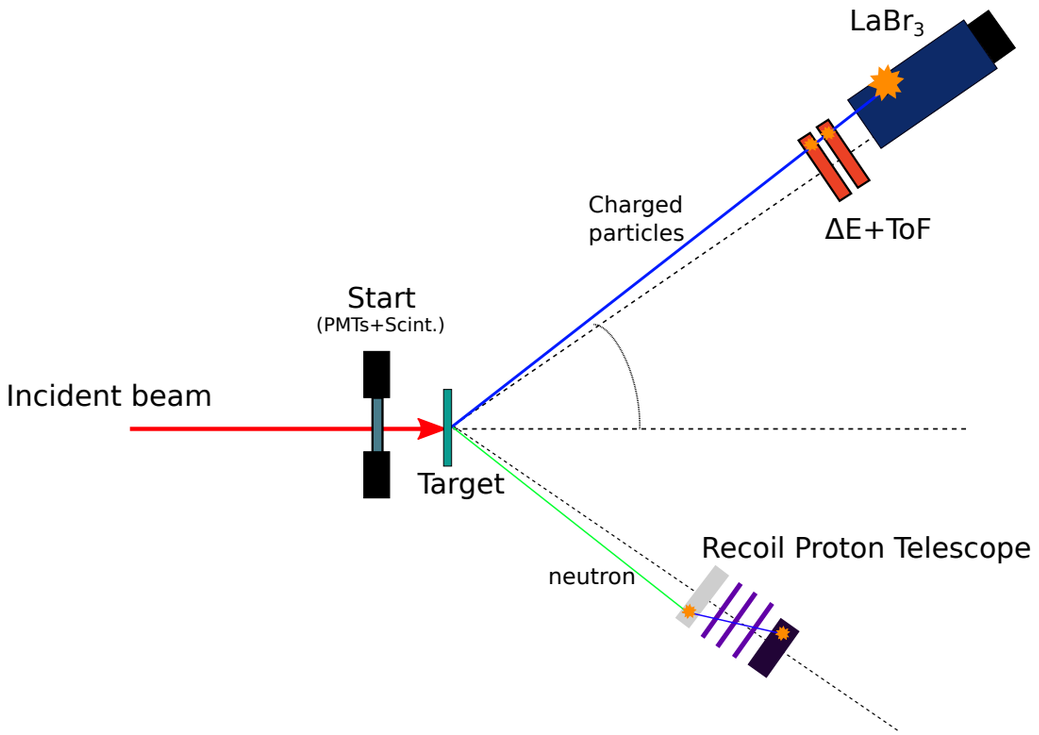
Space radiation protection

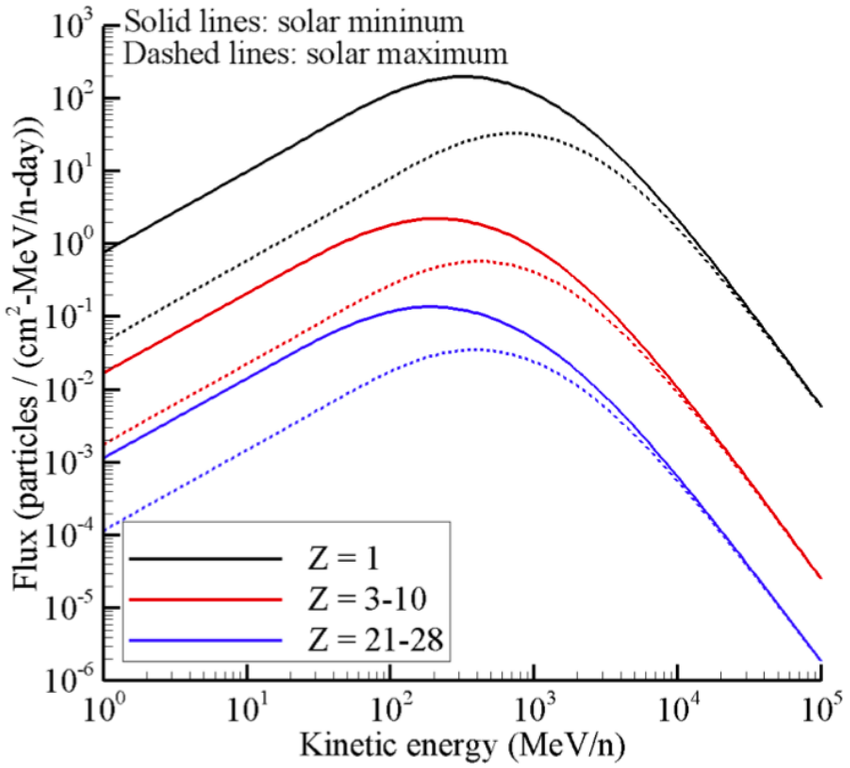
- CLINM (Cross-sections of Light Ion and Neutron Measurements) : cross-sections measurements with incident beams of ^{4}He, ^{12}C, ^{16}O,…, ^{56}Fe from 400 MeV/u (GSI-SIS) to 4 GeV/u (FAIR)



Space radiation protection

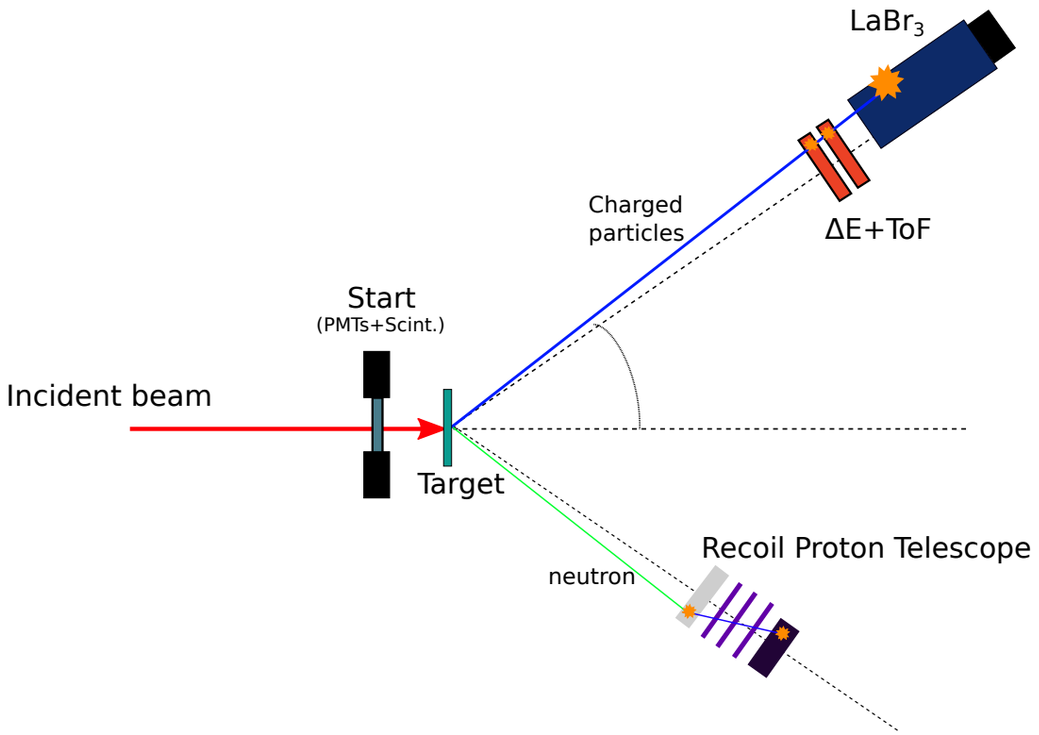
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  - Neutrons measured by RPT (Recoil Proton Telescope)

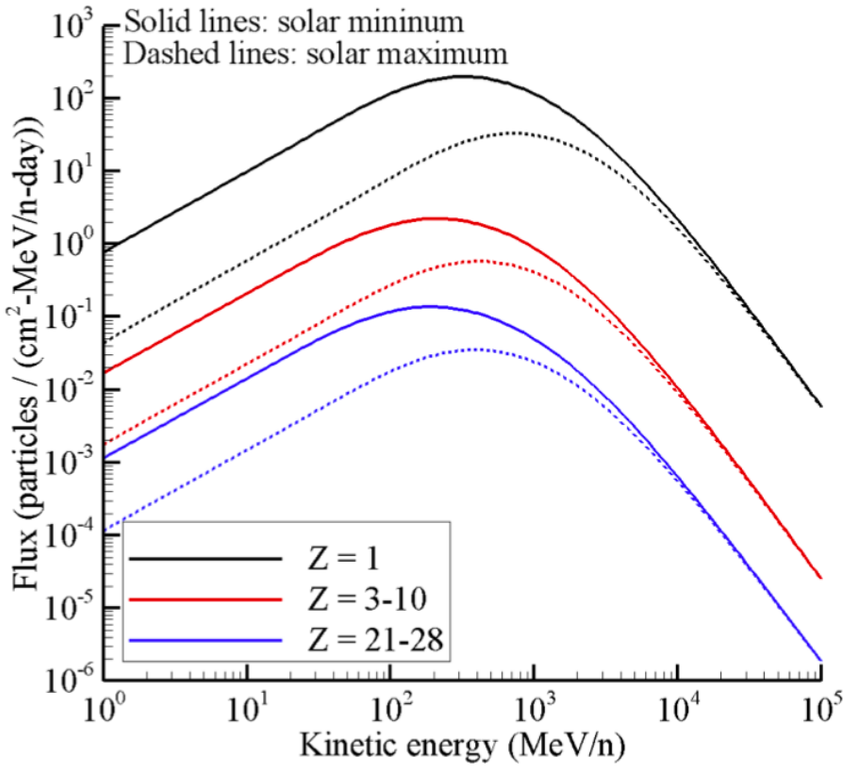




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  - ΔE-ToF telescope (plastic scint.) for charged particles identification
  - Neutrons measured by RPT (Recoil Proton Telescope)
- Integration of measured xs in MC codes (e.g. GEANT4)





Scientific background

- Many production cross-sections of **radioisotopes** ($^{44\text{-}47}$Sc, $^{64\text{-}67}$Cu, $^{149\text{-}155}$Tb, ^{223}Ra, ^{225}Ac, ^{226}Th,…) already measured @ **ARRONAX**

18 publications

- Differential cross-sections measurements of **^{12}C** (**50** and **95 MeV/u**) on thin targets measured @ **GANIL**
  Data available on http://hadrontherapy-data.in2p3.fr

7 publications

- Differential cross-sections measurements of **^{12}C** (**400 MeV/u**) on gold target @ **GSI** with the **FIRST** collaboration

2 publications

- Active participation in the international **FOOT** (FragmentatiOn Of Target) collaboration, first beam test in April 2019 @ **GSI** (**^{16}O**, **400 MeV/u** on ^{12}C target)

8 publications

+ Members of International Biophysics Collaboration (Ch. Finck, M. Vanstalle)

Contributors & teams

- GIP ARRONAX
  - F. Haddad, C. Koumeir, F. Poirier
- Subatech
  - A. Guertin, F. Haddad, N. Michel, T. Sounalet
- GANIL
  - X. Ledoux
- LPC Caen
  - M. Labalme, S. Salvador
- IPHC
  - Nuclear energy team: M. Kerveno, G. Henning, P. Dessagne
  - Hadrontherapy & DESIS teams: N. Arbor, Ch. Finck, S. Higueret, D. Husson, M. Vanstalle

Backup slides

N. Arbor, P. Dessagne, C. Finck, A. Guertin, F. Haddad, S. Higueret, D. Husson, M. Kerveno, C. Koumeir, M. Labalme, X. Ledoux, F. Poirier, S. Salvador, T. Sounalet, M. Vanstalle

05/02/2020

TALYS

TALYS default and adjusted calculations

TALYS code version 1.9

the combination of models that best describes the whole set of available data for all projectiles, targets and incident energies defined by the TALYS authors

⇨TALYS 1.9 Default

One combination of models that best describes our whole set of data for proton, deuteron, alpha particles as projectile (and also some literature data) has been defined by A. Guertin et al.

⇨TALYS 1.9 Adj.

Models	Projectile	Default	Adj.
Optical	p (1)	A.J. Koning and J.P. Delaroche (2003)	A.J. Koning and J.P. Delaroche (2003)
	d (5)	S. Watanabe (1958)	Y. Han et al. (2006)
	α (8)	V. Avrigeanu et al. (2014)	Demetriou et al. (2002)
Pre-equilibrium	All (4)	Two-component exciton model Numerical transition rates with E-	Two –component exciton model Numerical transition rates with optical
Level density	All (6)	Constant temperature and Fermi gas model	Microscopic level density (Skyrme force) from Hilaire's combinatorial tables

SPIRAL2

26 accelerating cavities, enclosed in 19 niobium cryomodules cooled by liquid helium

Energies ranges:

33 MeV for protons
40 MeV for deuterons
< 14.5 MeV/A for heavy ions

High intensities:

up to 5 mA for deuterons
< 1mA for heavier ions

beam	P+	D+	ions	ions
A/Q	1	2	<3	<6 or 7
Max. I (mA)	5	5	1	1
Min. output E (MeV/A)	2	2	2	2
Max output E (MeV/A)	33	20	14.5	8
Max. beam power (kW)	165	200	44	48

Beam production

2 ion sources: ECR4 & ECR4M, Q/A ~ 1/9 à 1/3
Surface ionization (SPIRAL1)
1 ECR ion source, type Phoenix Booster (SPIRAL1)
2 sources: ECR Q/A 1/3 and protons/deutons (SPIRAL2)

ECR type NanoganIII (SPIRAL1)
1 FEBIAD Source (SPIRAL1)
1 ECR GTS Source (R&D)
Laser Source (R&D)

NFS

The **NFS facility** is composed of two main areas, a **converter cave** and a time-of-flight (**TOF**) area



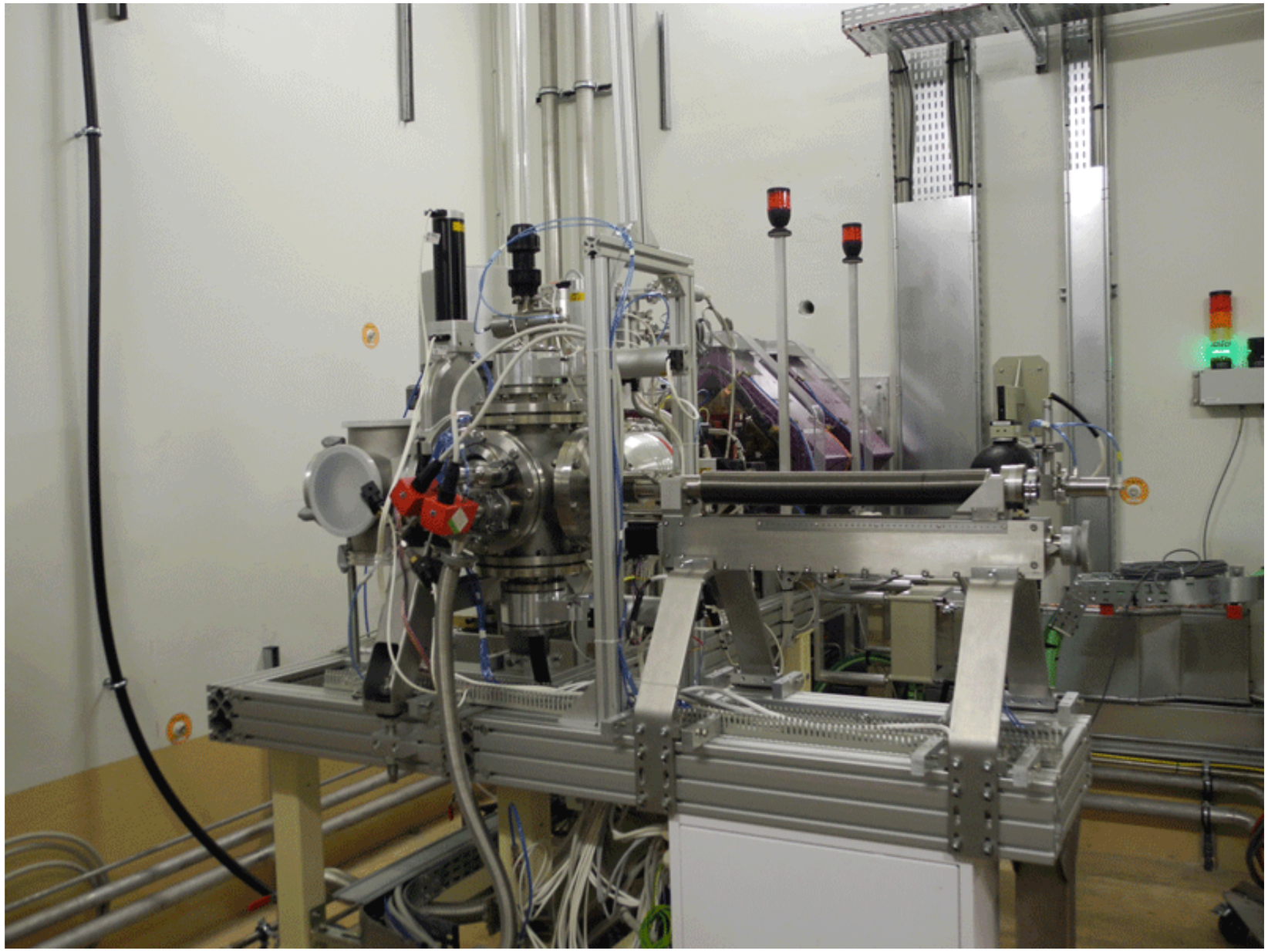


NFS accept **any beam** and **any energy** from previous table
But **power limitation above 2 kW** to be discuss on a case by case approach

Induced reactions by neutrons (n,2n), (n,α) … can be studied up to 40 MeV
Induced reactions by light ions (p, d, α, Li …) up to few tens of MeV

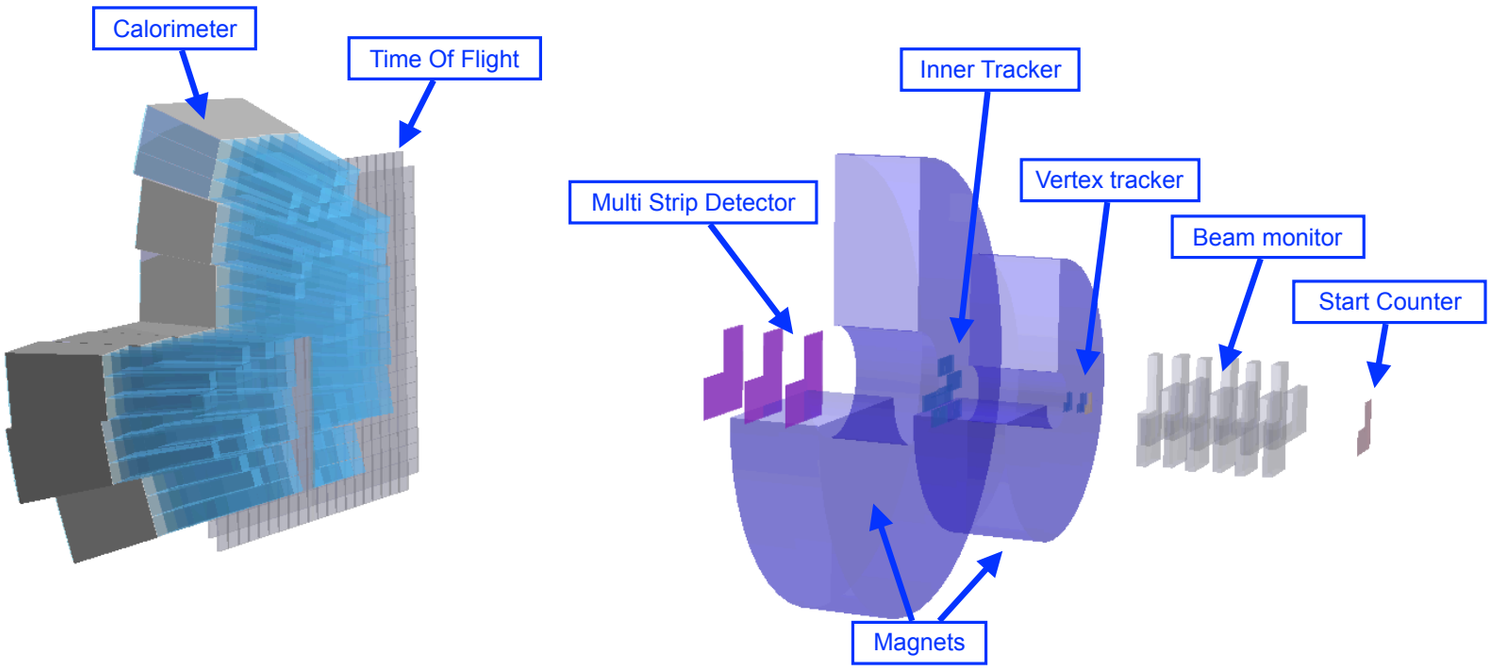
NFS

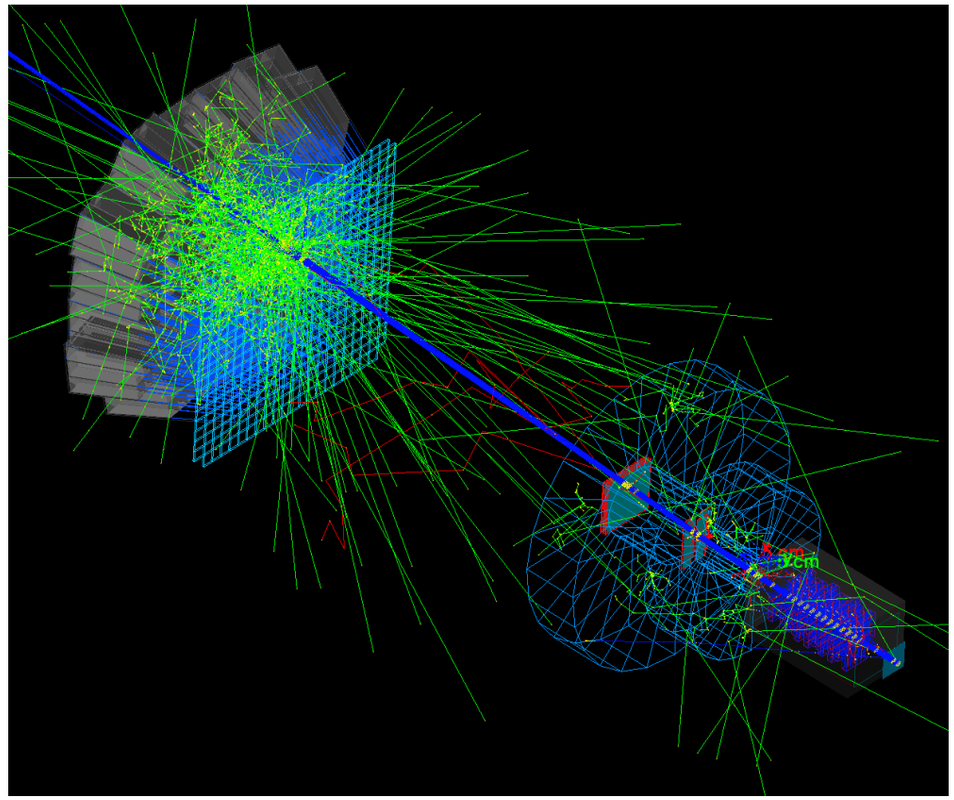
- The irradiation station @ NFS: proton, deuteron or ions



Measurement of cross-sections

- FOOT (FragmentatiOn Of Target) experiment aims at measuring cross sections of ^{12}C, ^{16}O @200-700 MeV/u
  - 10-20° acceptance
  - First measurements with BM, VTX and TOF wall in April 2019 (GSI)

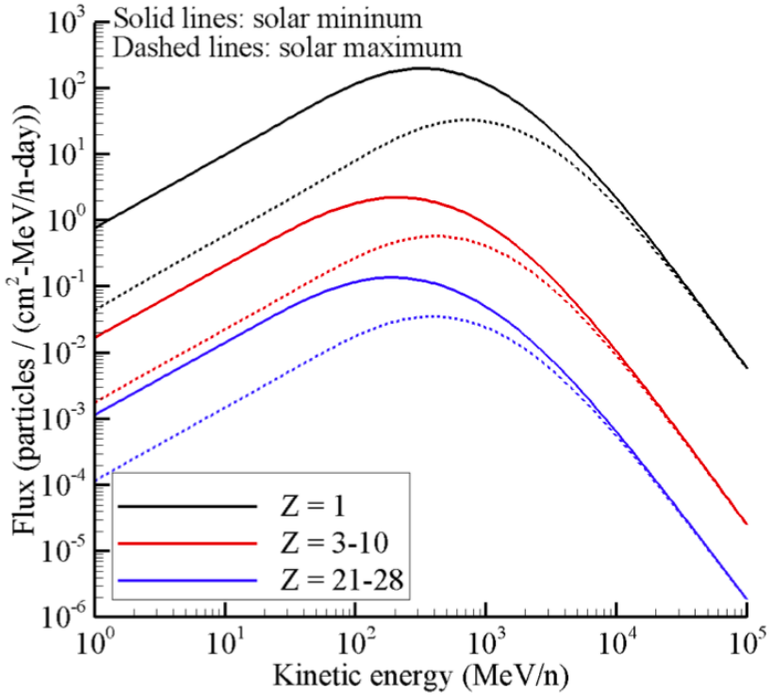


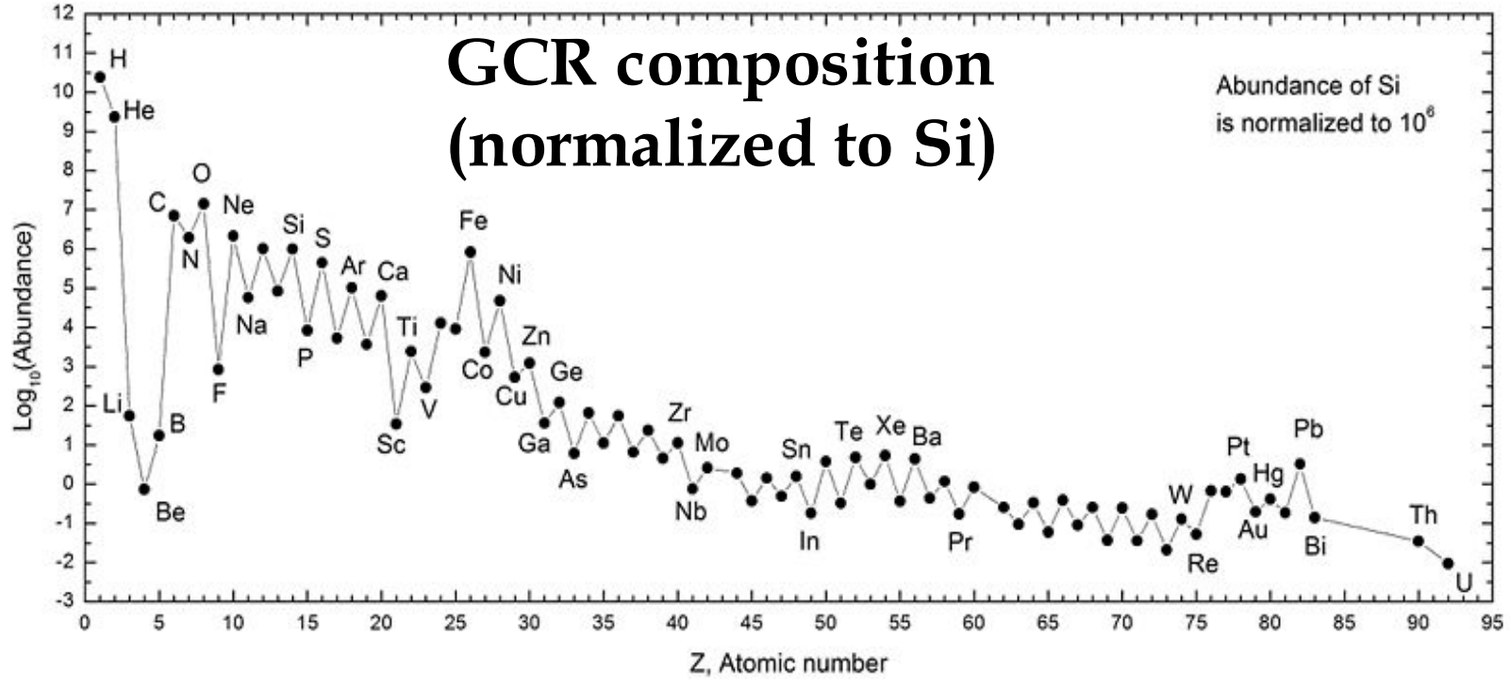


GEANT4 simulated setup

Space radiation protection

- Energy spectrum of GCR peaked ~ 1 GeV/u
- Important Z range: from ^{1}H to ^{238}U





- Lack of cross-sections data ⇒ Need of measurements on tissue-equivalent + shielding targets