Physics for the stars at down-to-earth facilities

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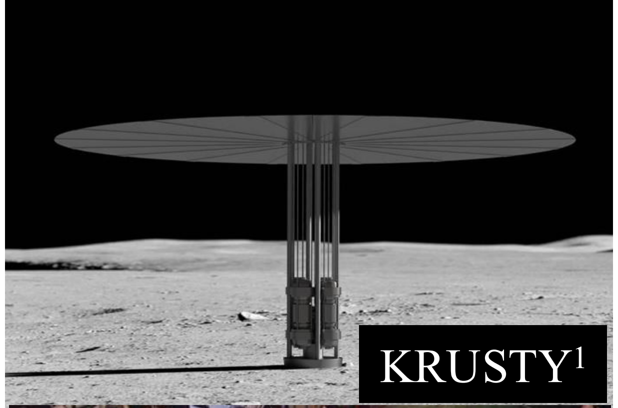
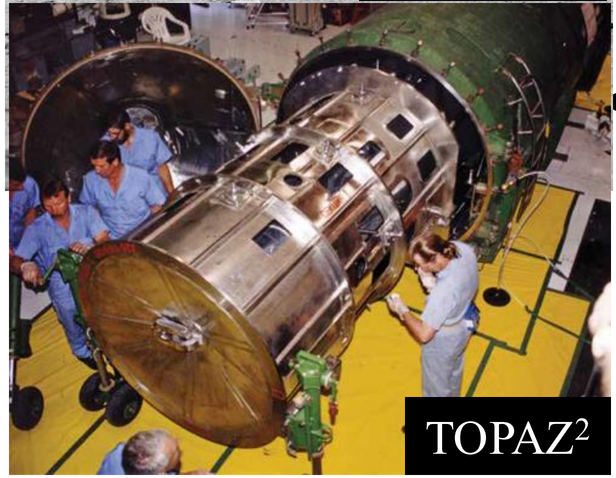
Space travel requires data & modeling to support the missions

Energy Production





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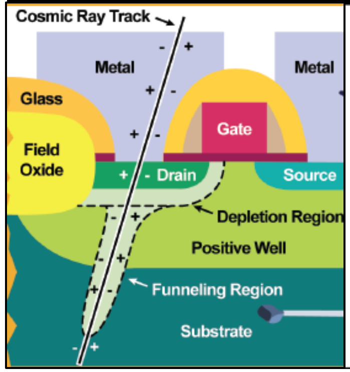
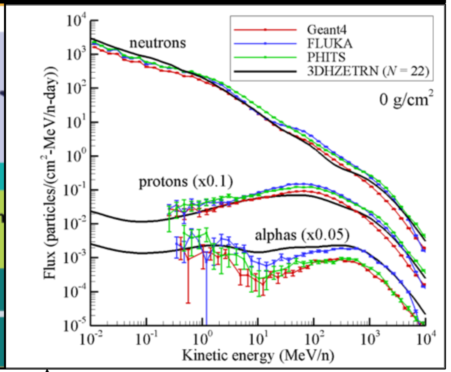
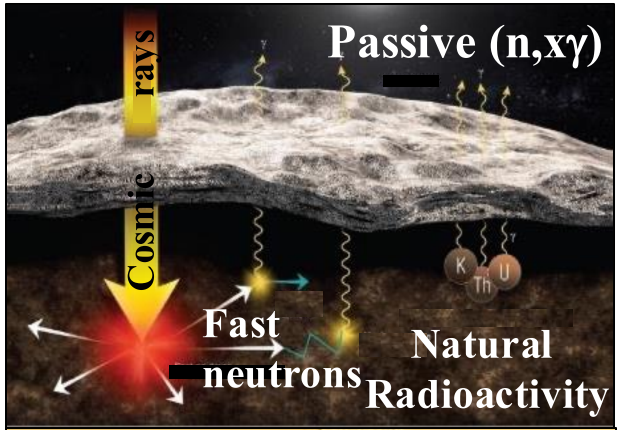
Dose/Shielding Calculations for Electronics and Humans





Data & Transport

Planetary Exploration



Nuclear Propulsion

Protecting spacecrafts and astronauts requires heavy-ion physics

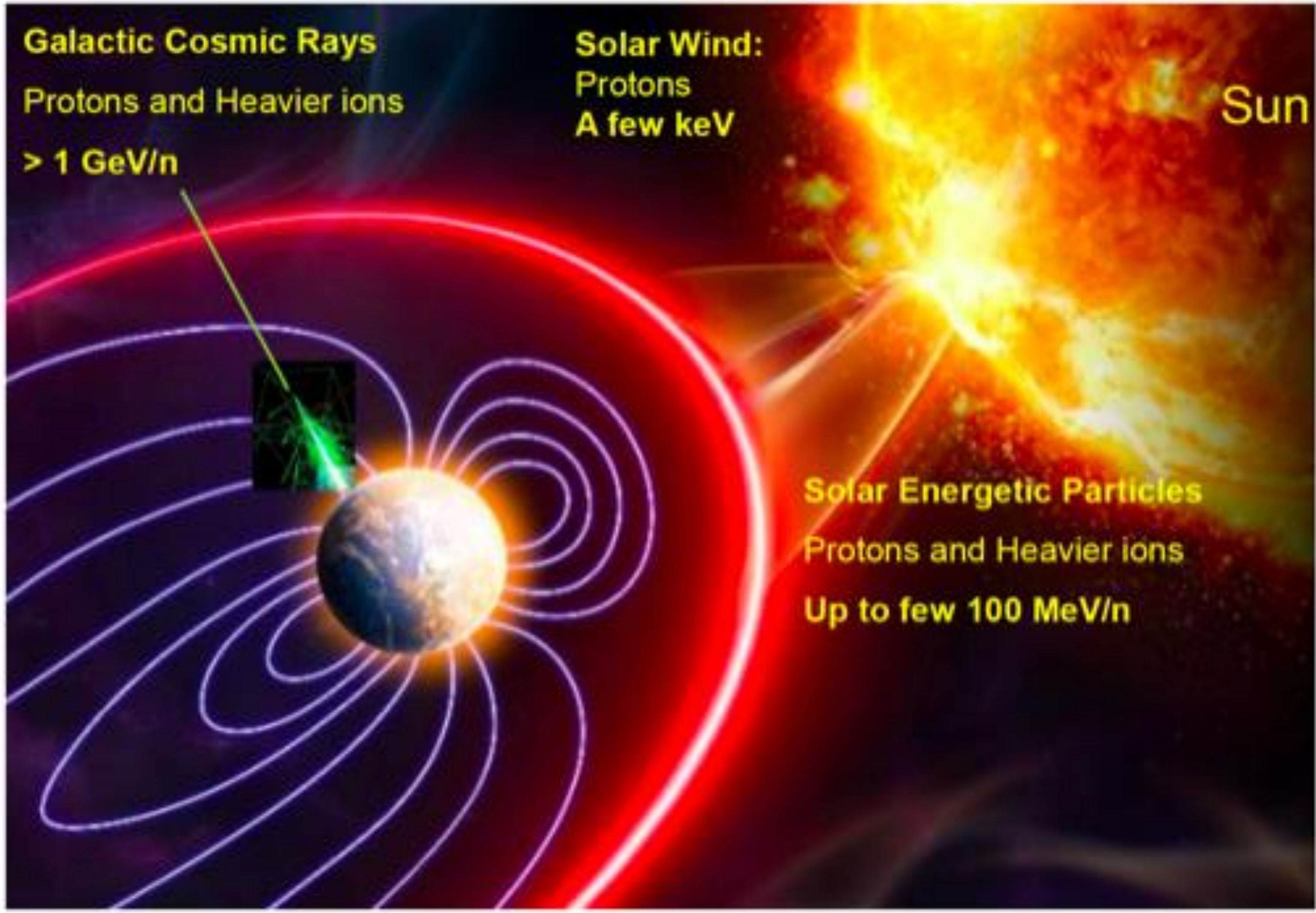
Space radiation == energetic charged particles

The origin of these particles determines their
Importance with respect to potential damage

Solar wind:
Protons up to a few keV, short range (μm)

Solar energetic particles:
Protons and ions up to 100 MeV/n, cm range

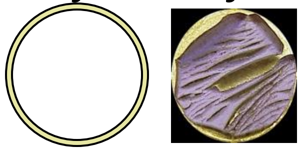
Galactic Cosmic Rays (GCRs):
Protons and heavy ions (up to Fe)
MeV-TeV energy scales,
Long range (hundreds of m),
Difficult to shield against ,
These interactions result in multiparticle production



What can go wrong? (near-Earth environment)

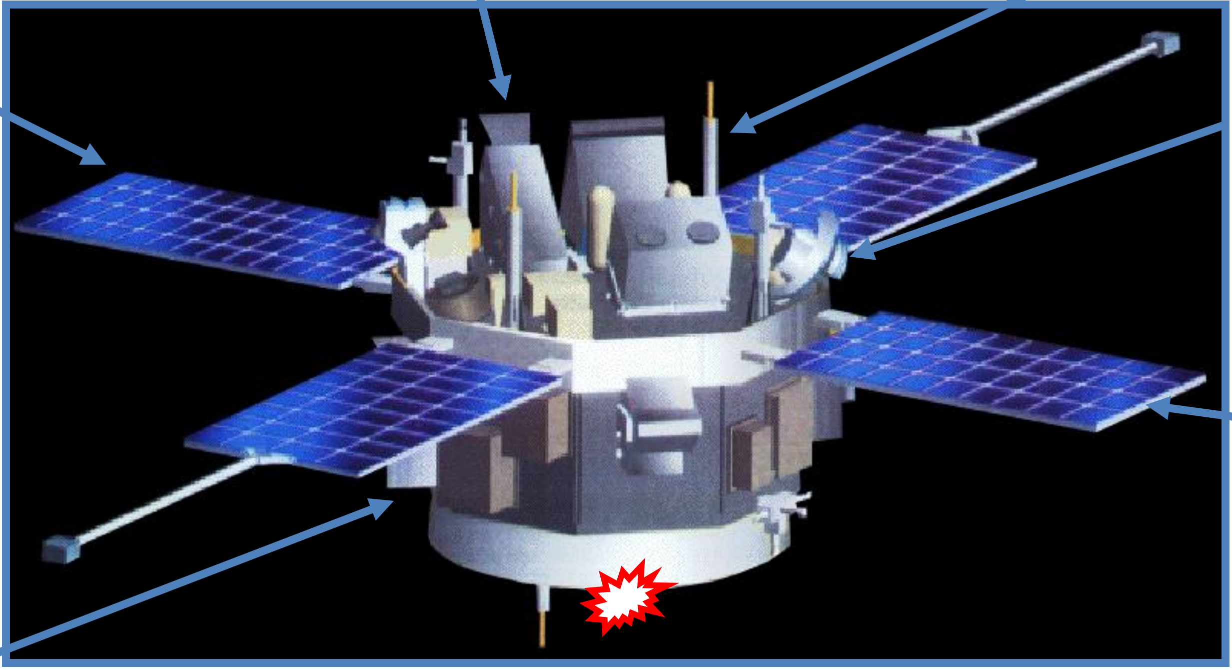
False stars in star tracker CCDs

before *after*



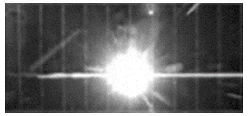
Surface degradation from radiation

Solar array power decrease due to radiation damage



Electronics degrade due to total radiation dose

Solar array arc discharge



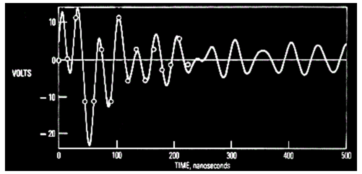
Single event effects in microelectronics

1101 => 0101

Spacecraft components become radioactive

Electromagnetic pulse from vehicle discharge

Induced Voltage



J. E. Mazur, J. F. Fennell, & P. O'Brien, Proc. 31st Annual AAS Rocky Mountain Guidance and Control Conference, vol. 131, M. E. Drews & R. D. Culp Eds., 2008

Effects of cosmic rays on electronics

- GCRs can cause *single event upsets* that can cause temporary or permanent failures.

- GCR heavy ions cause a local, dense ionization column

- Secondary p and n can induce reactions that create a recoiling residual nucleus

- The imparted dose depends on the *stopping power* (energy loss in matter by another name) of the recoiling nuclei.

- Stopping powers calculated using Bethe-Bloch equation – similar to detector dE/dx

Determining radiation effects on humans (Dose)

$$\text{Dose (D)} = \frac{\text{energy deposited}}{\text{mass of material}}$$

$$\text{Dose Equivalent} = \text{D} \times \text{Q (rem) (1 Sievert (Sv)} = \text{100 rem)}$$

$$\text{Q}_{\gamma-\text{rays}} = 1, \text{Q}_{\alpha} = 20$$

- Normal Background Dose/day on earth: 10 μSv
- **Lowest annual dose linked to cancer: 100 mSv**
- **DOE Limit for first responders: 250 mSv**
- Acute dose causing symptoms: 400 mSv
- **10 minutes next to the Chernobyl core: 50 Sv**

What are types and energies of cosmic rays?

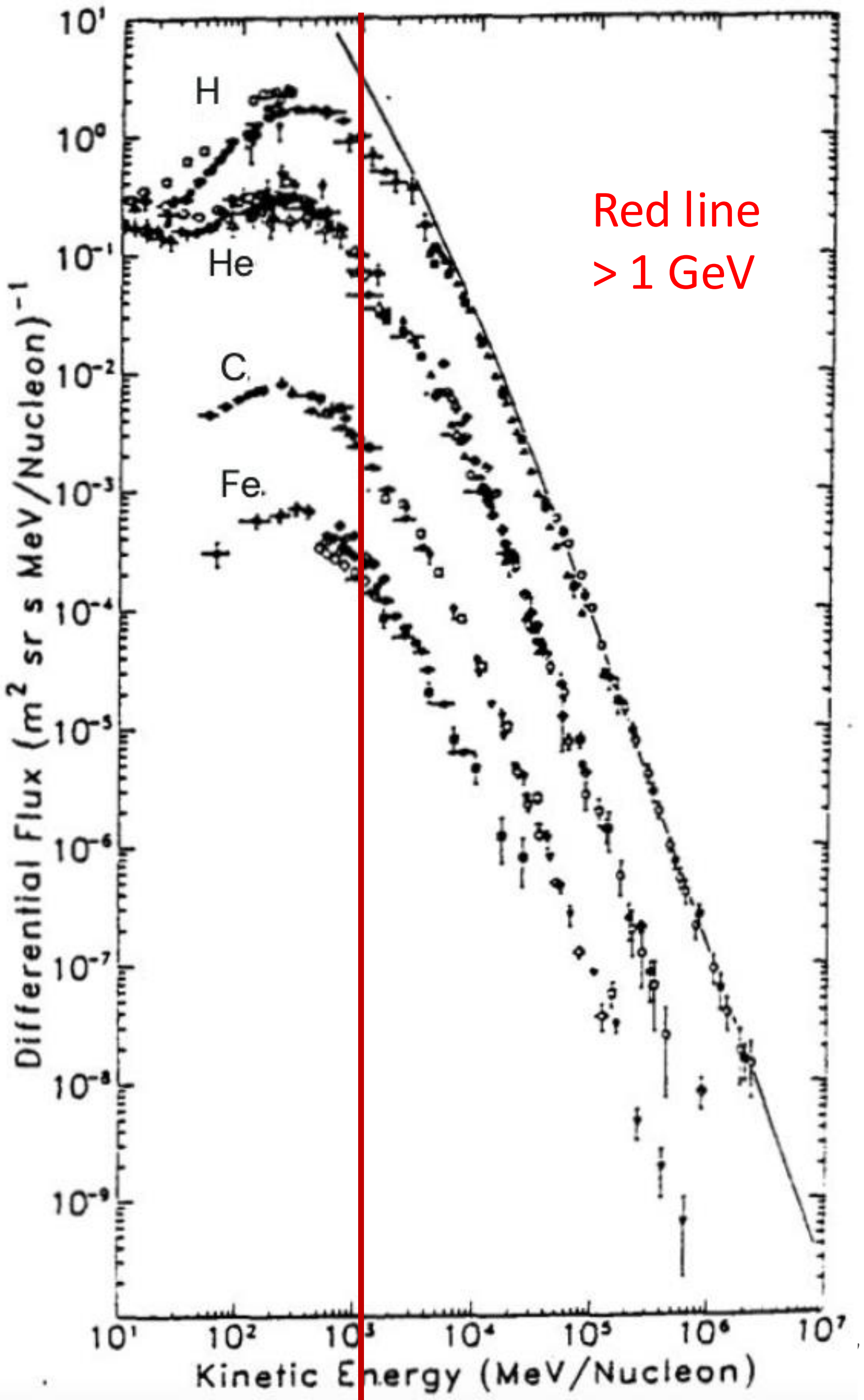
Galactic cosmic rays include everything from protons to heavy nuclei (up to ^{56}Fe) with KE exceeding 50 GeV/A: peak flux ~ 100 MeV - 1 GeV

The cosmic ray flux is composed of nuclei (90% protons, 9% He, and 1% nuclei up to Fe).

A 1 GeV proton can travel 1 m through Al so shielding spacecraft and satellites is nontrivial

Protons deposit energy more locally while neutrons travel further

The type of shielding contributes to the total multiplicity of secondaries



What do these secondaries look like?

When a cosmic ray strikes the atmosphere, or rather a nucleus like N or O in the atmosphere, it triggers a cascade of particles, both hadronic and electromagnetic, similar to those seen in high energy collisions governed by QCD: fragment nuclei, n, p, π, K, e, μ

Detectors often calibrated by exposure to cosmic rays muons from the upper atmosphere (ALICE collab, 2010 *JINST* **5** P03003)

When such a cosmic ray strikes a spacecraft or satellite, it can trigger a similar cascade but now through spacecraft shielding, electronics, computers, and astronauts

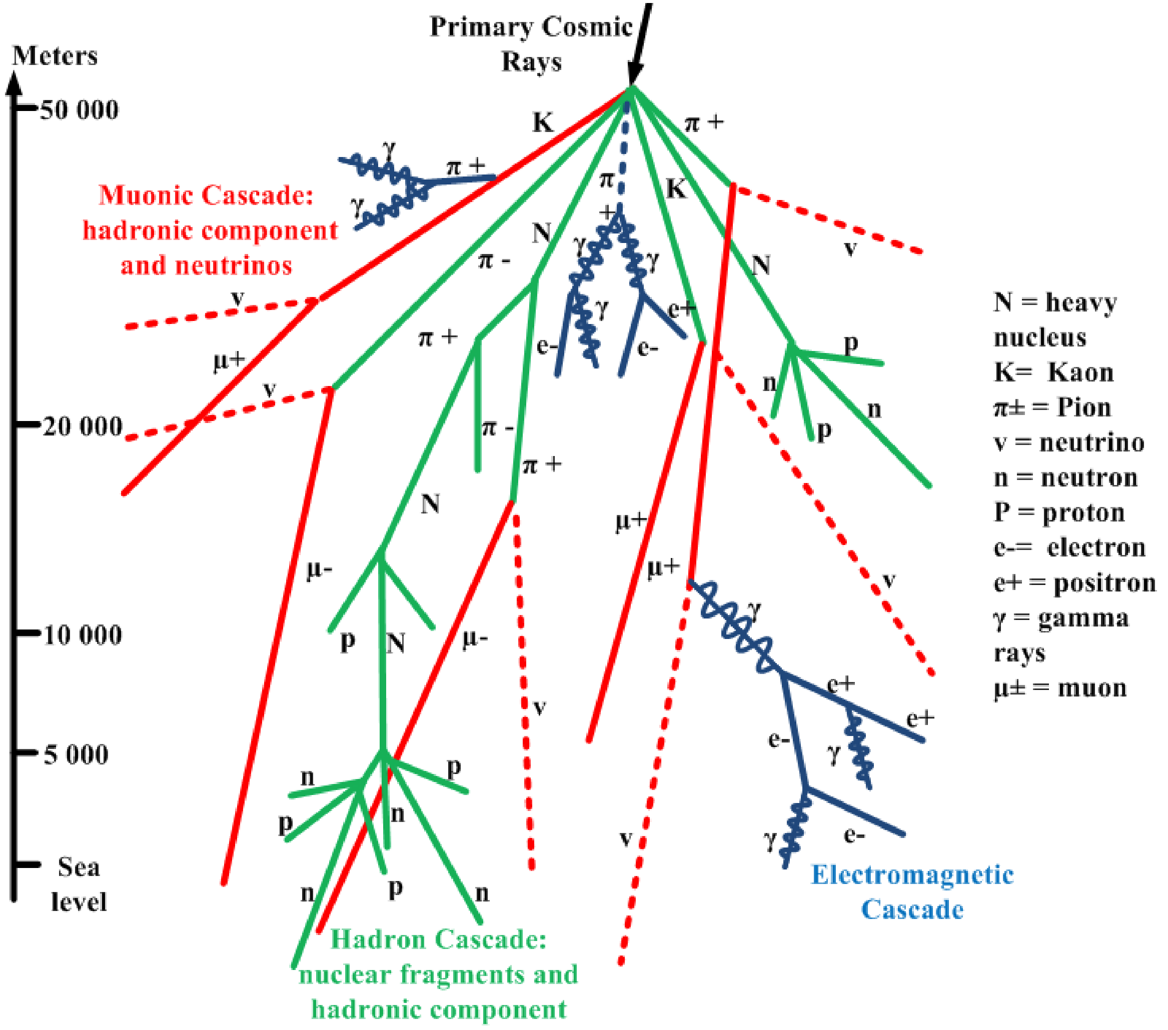


Diagram by Daniel Gomez Toro

Energy deposition (stopping power) in material quantified by linear energy transfer

Linear Energy Transfer is the ratio of energy transferred by a charged particle to target atoms along its path, *dE/dx*.

As $E \rightarrow 0$, the stopping power increases, leading to a *Bragg Peak* where the highest dose is deposited

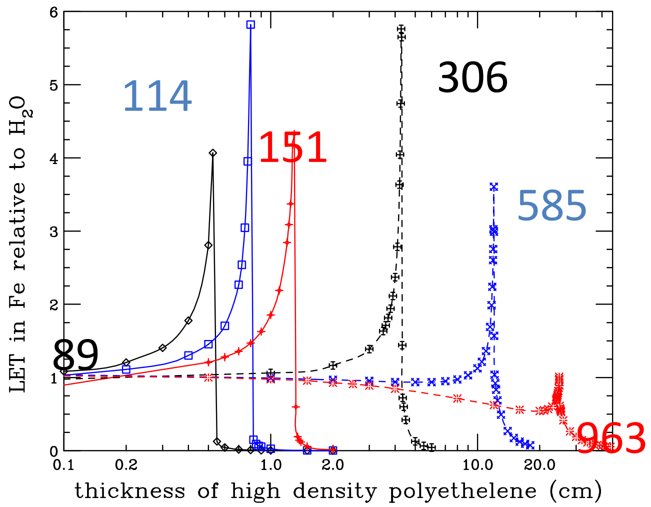
Higher-*Z* ions have shorter ranges and higher dose in their Bragg Peaks

Higher-energy ions are longer range, requiring more material to stop them

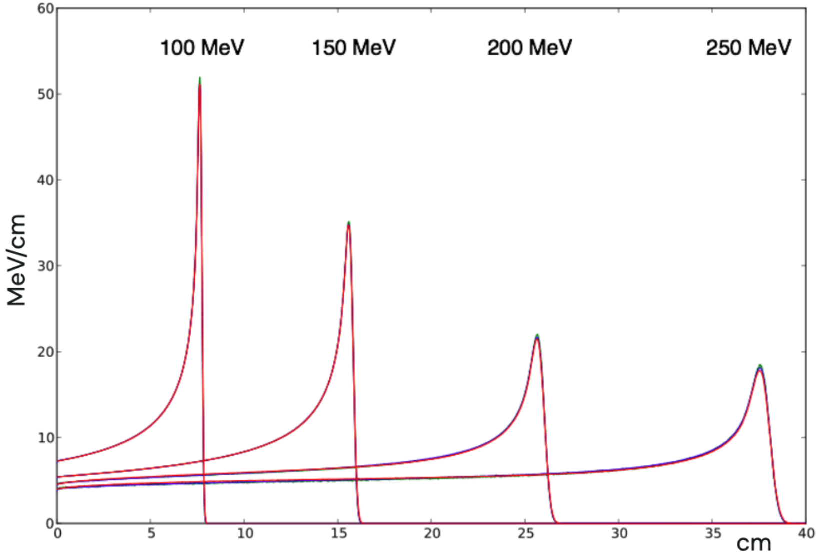
Need: balance shielding required against damage and dose

At some sufficiently high energy, the shielding becomes more like a hadron calorimeter, stopping all particles but muons

Stopping power of Fe in polyethelene for a range of energies (in MeV), BNL NSRL

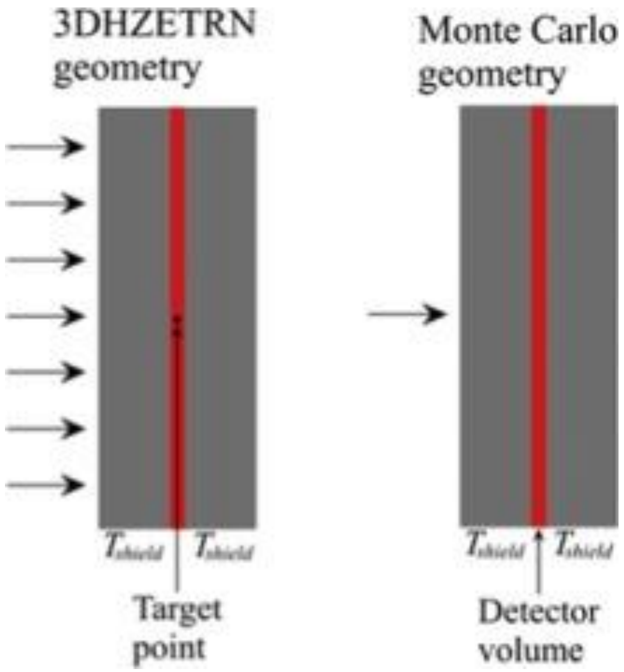


Penetration depth of proton in water at various energies



Model-based calculations of shielding and dose

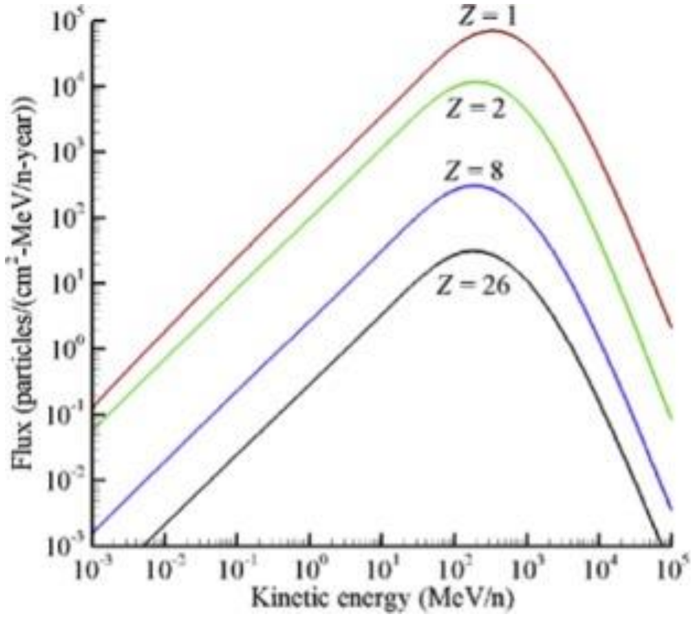
Slaba *et al*, Life Sciences in Space Research **12** (2017) 1-15



Galactic cosmic rays incident on a geometric slab with shielding materials, aluminum and polyethylene, on both sides of an 0.3 mm water layer used to obtain a meaningful evaluation of radiation dose and dose equivalent from the models (top right)

3DHZETRN is deterministic NASA code using different assumptions:
N=1 1D straight ahead linear interactions
N=2 1D treatment but allowing forward-backward motion
N=34 3D transport for neutrons and neutron-induced light ions

Monte Carlo models used were: MCNP6 (neutron transport), PHITS (MC for space radiation studies), FLUKA (with DPMJET-III), and Geant4 with two heavy-ion models (QMD and INCLXX)

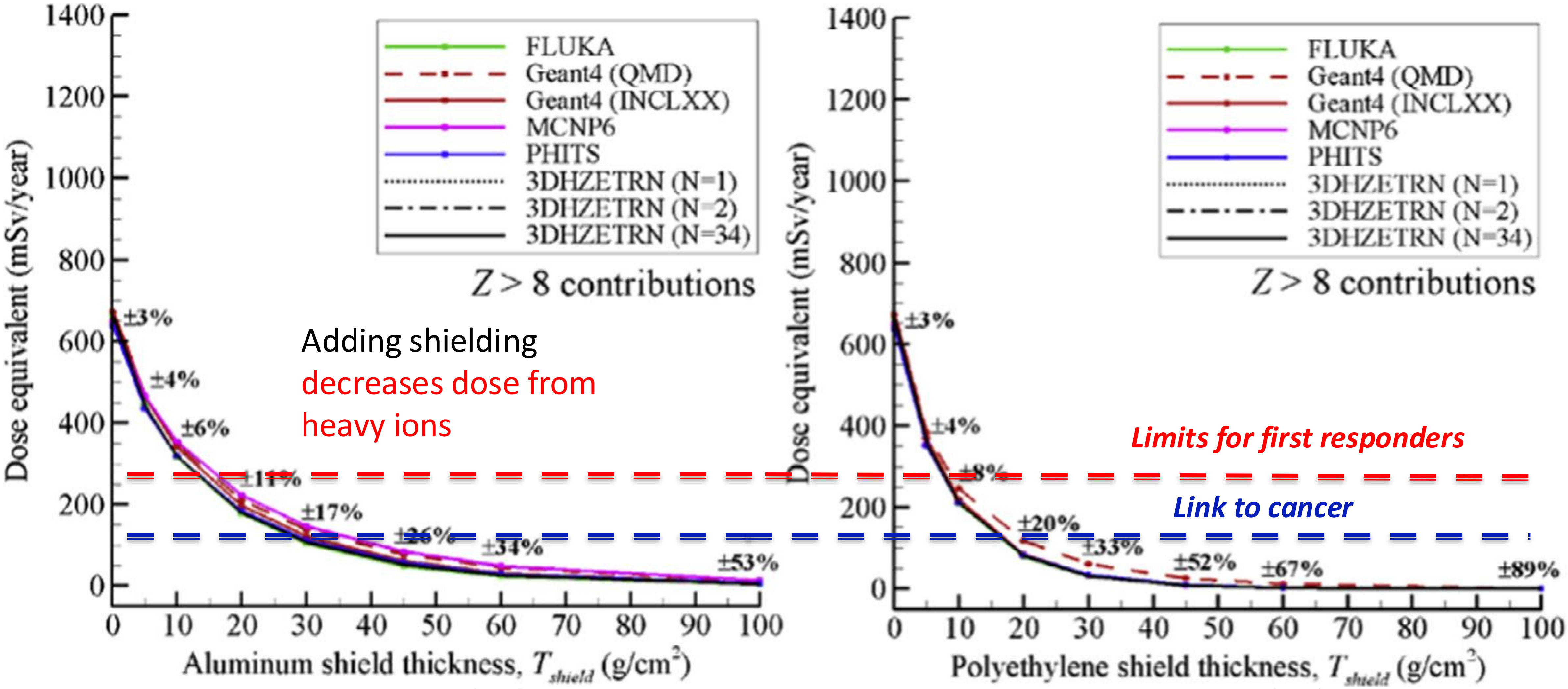


Lower right plot shows the galactic cosmic ray spectra used for ions with Z = 1, 2, 8, and 26 used to generate flux on target materials in the models

Dose equivalents are shown for different different primary and secondary particles at target thicknesses and compared to radiation dose limits

Results for ions with Z > 8

%s represent average individual model uncertainties; Z > 8 dominated by primary ions and projectile-like fragments

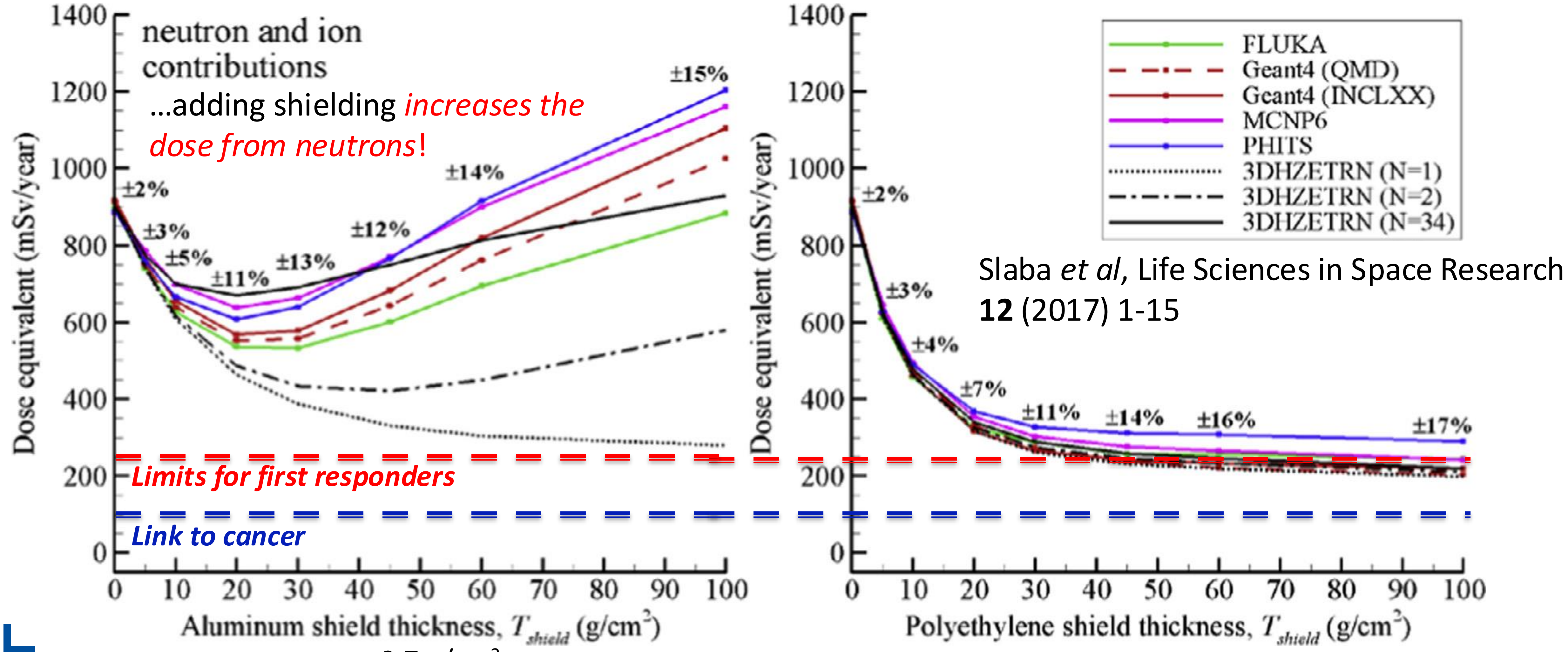


ρ_{Al}=2.7 g/cm^3 ρ_{PE}=0.97 g/cm^3

T.C. Slaba et al. Life Sciences in Space Research **12** (2017) 1–15

Neutrons and light ions difficult to shield against

Very large range of model results for neutrons and Z = 1, 2 cosmic ray fluxes – indeed in general adding Al shielding increases the dose for secondary neutrons. Proton contributions are mostly from initial flux but 25% comes from secondary protons from p+A inelastic interactions. This dose is deadly!



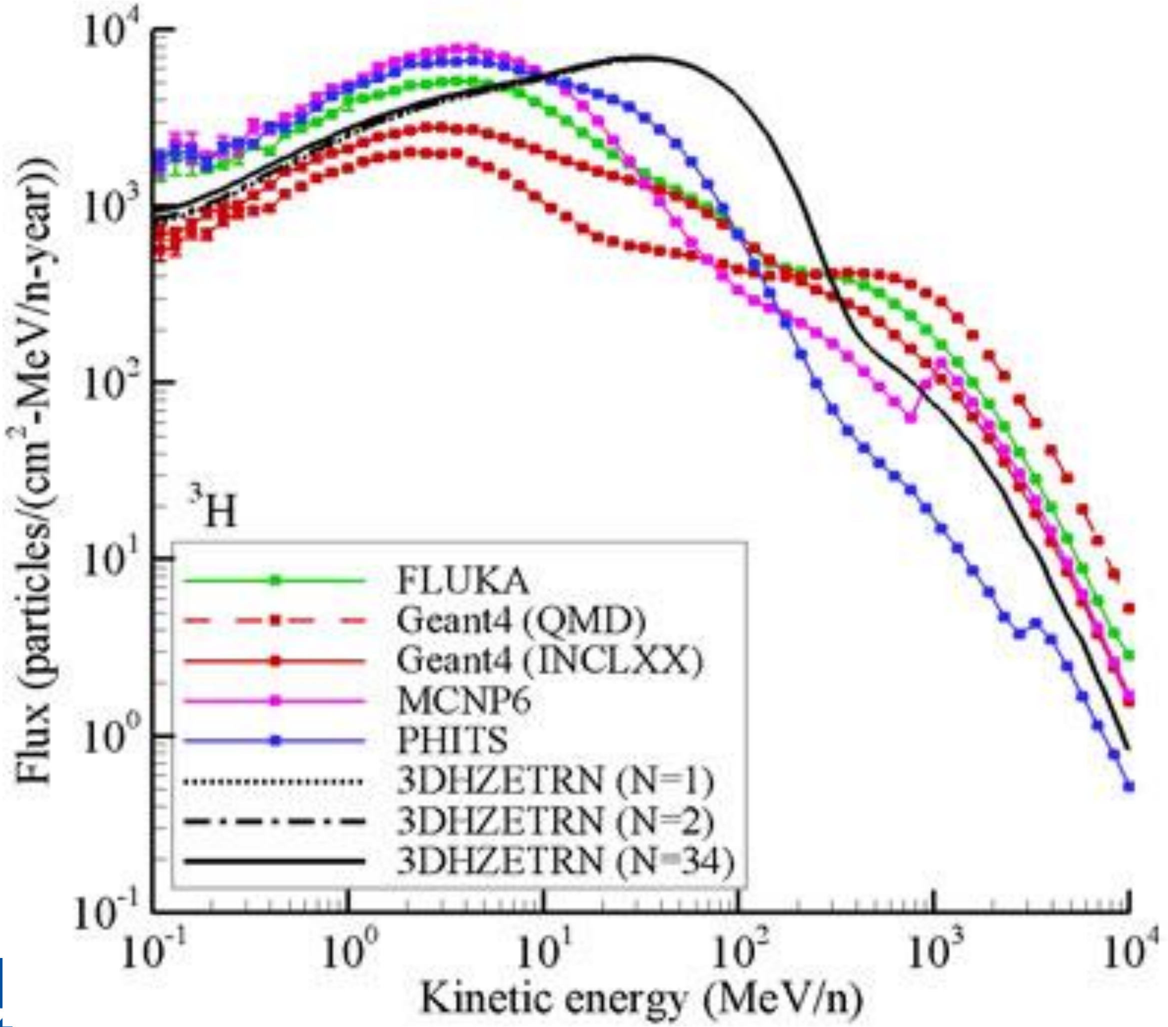
Slaba *et al*, Life Sciences in Space Research **12** (2017) 1-15

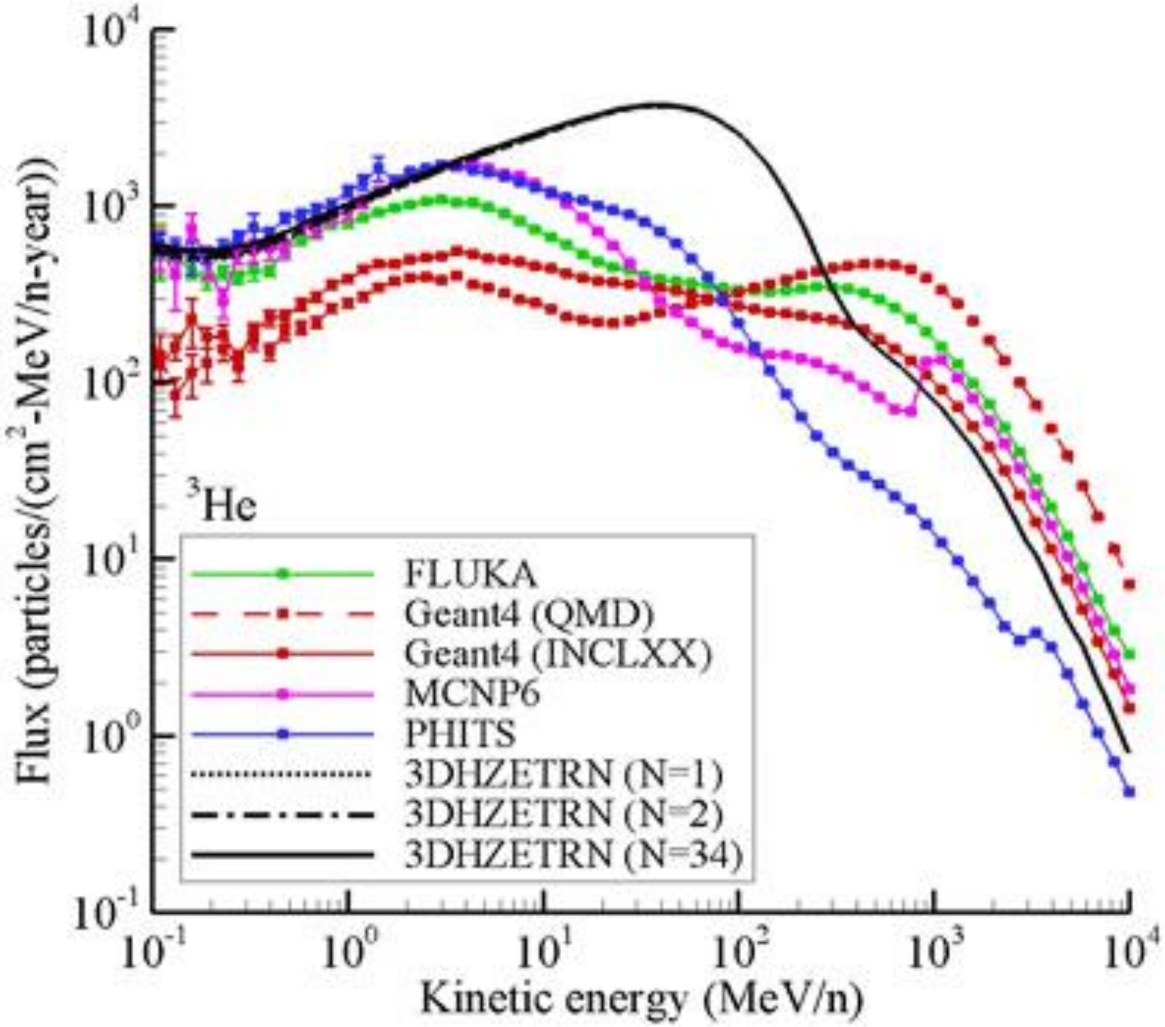
ρ_{Al}=2.7 g/cm^3

ρ_{PE}=0.97 g/cm^3

Wide model disagreement for ^{3}H and ^{3}He production

Model disagreements are mainly due to inaccurate light ion nuclear physics models and lack of experimental data to improve these models



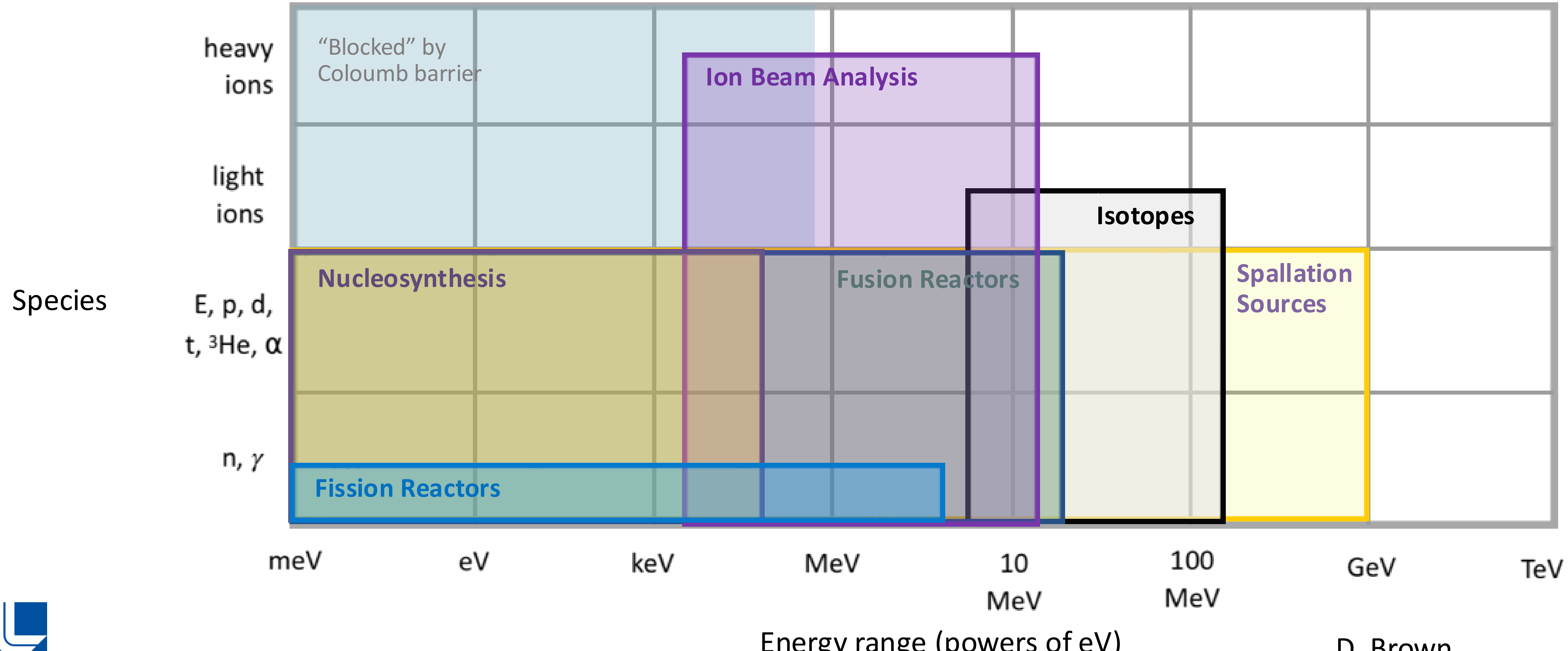


Nuclear data are needed to meet these needs

Where does data for modeling cosmic ray interactions come from?

Standard nuclear databases cover mostly neutron-induced reactions (and some charged particles) up to about 20 MeV; need to go WAY beyond that

Essentially NO data for *E* > 3 GeV



D. Brown

Nuclear data is interwoven throughout all of nuclear physics

Hadron-related physics touches space and medical applications in particular

Fewer codes are available to deal with the energies and species appropriate for these applications

Note that RHIC is included as a data facility

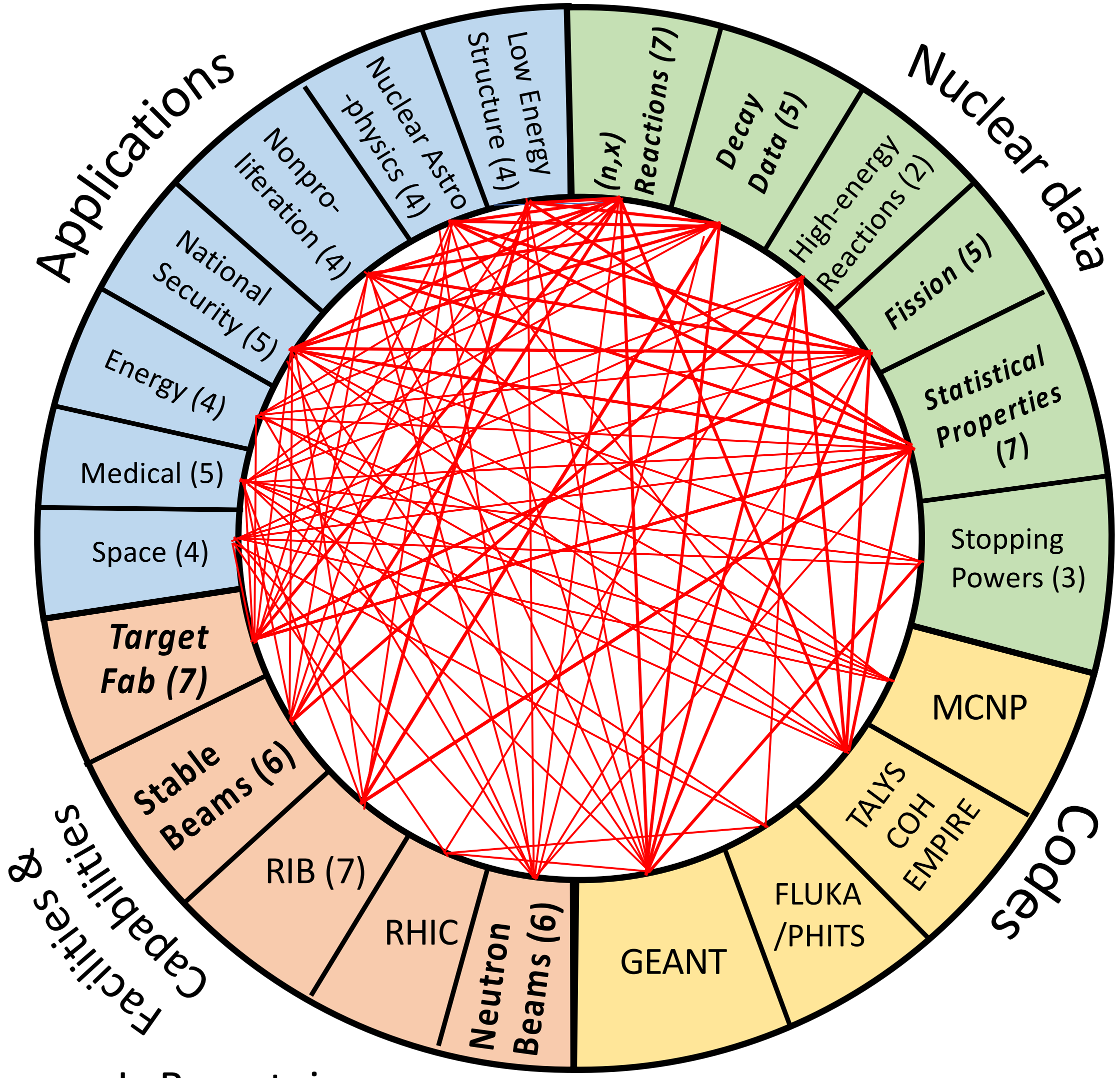


Diagram by A. Spyrou, L. Bernstein

Heavy-ion physics already depends on nuclear data

- Transport/interaction of particles in detector material is of paramount importance in all physics experiments and also in accelerators, medical applications:
  - Experiment design: material budget, energy loss/stopping power, energy and position resolution, radiation levels, tolerances
  - Monte Carlo corrections to data: material budget, particle tracking (multiple scattering, momentum resolution), energy loss, conversion
- Most commonly used packages: Geant3, Geant4, FLUKA utilize information taken directly from Nuclear Data libraries
- Theoretical calculations use nuclear data on nuclear shapes, charge distributions; has influenced Glauber models, isobar runs, Au+Au *vs*. U+U comparison, flow calculations

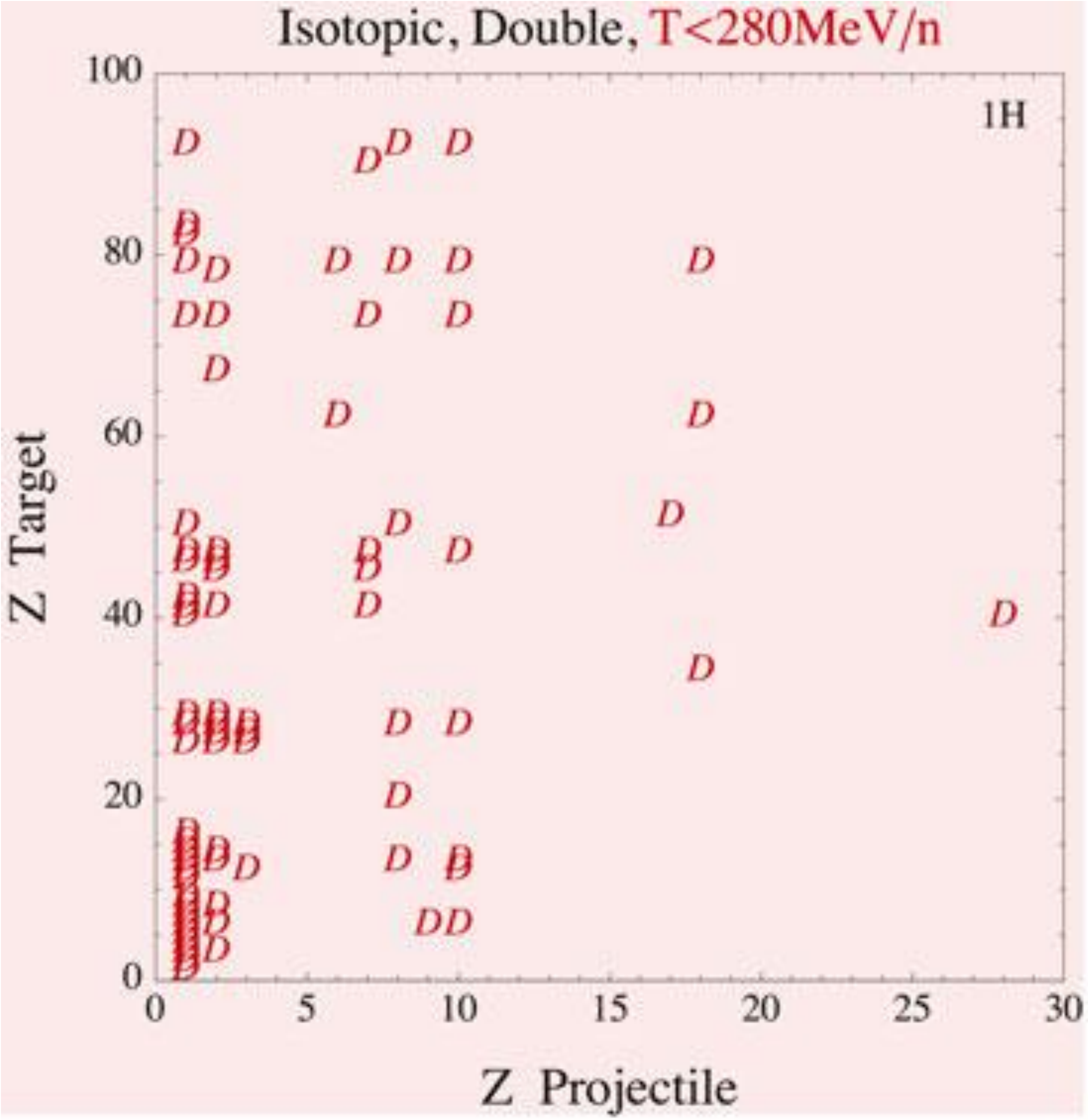
Nuclear data needs related to space radiation protection

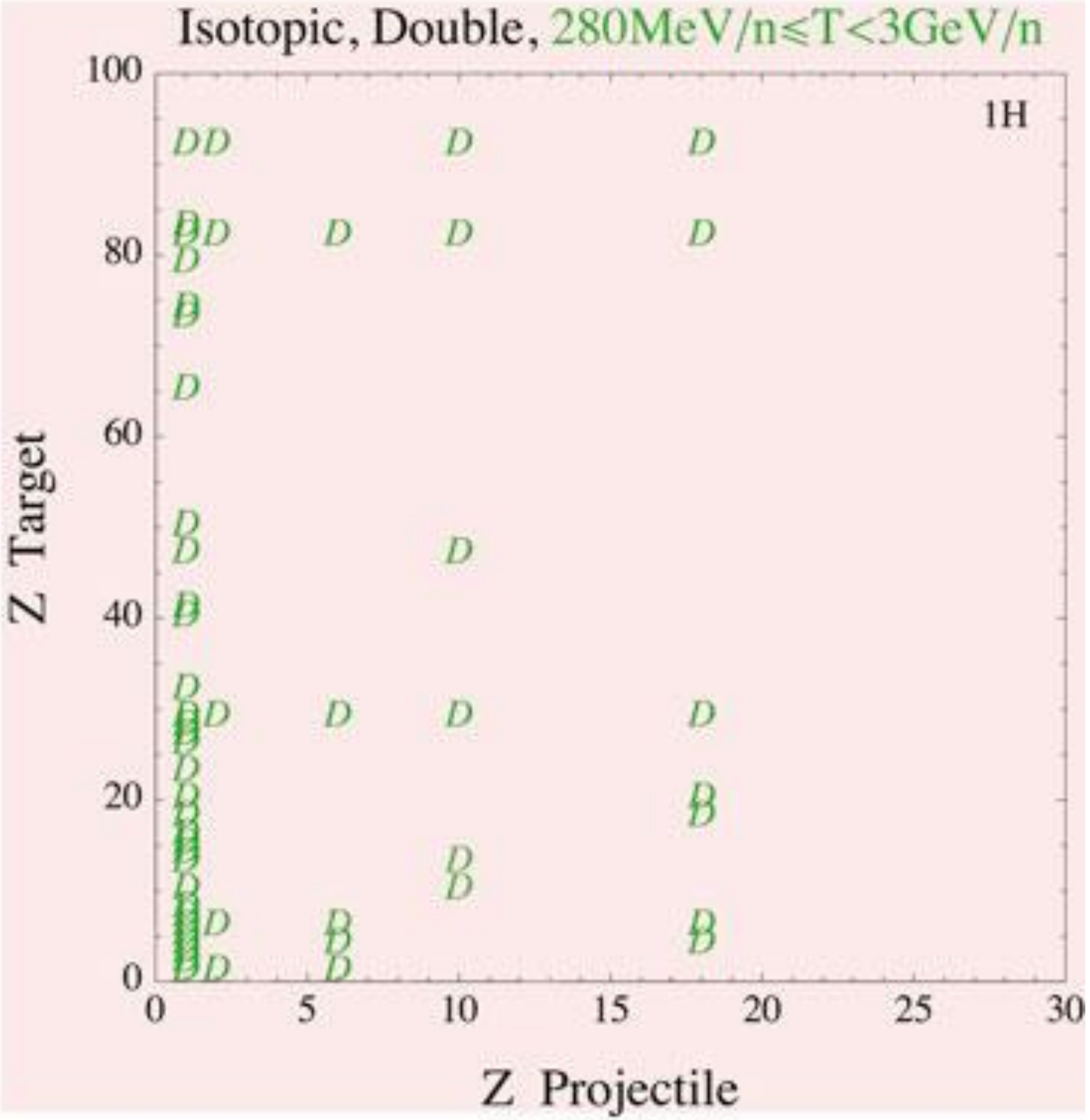
J. Norbury et al., Front. Phys., 29 November 2020, Sec. Medical Physics and Imaging
Volume 8 - 2020 | https://doi.org/10.3389/fphy.2020.565954

- Beam energy range of interest: 50 MeV/n – 50 GeV/n
- Projectiles of interest: He, C, O, Si, Fe (high intensity in the galactic cosmic ray flux)
- Targets of interest: H, C, O, Al, Fe (commonly used materials in space exploration)
- Observables of interest: double differential cross sections for pi, p, d, t, ^{3}He, ^{4}He
- Also needed: model development and transport code validation

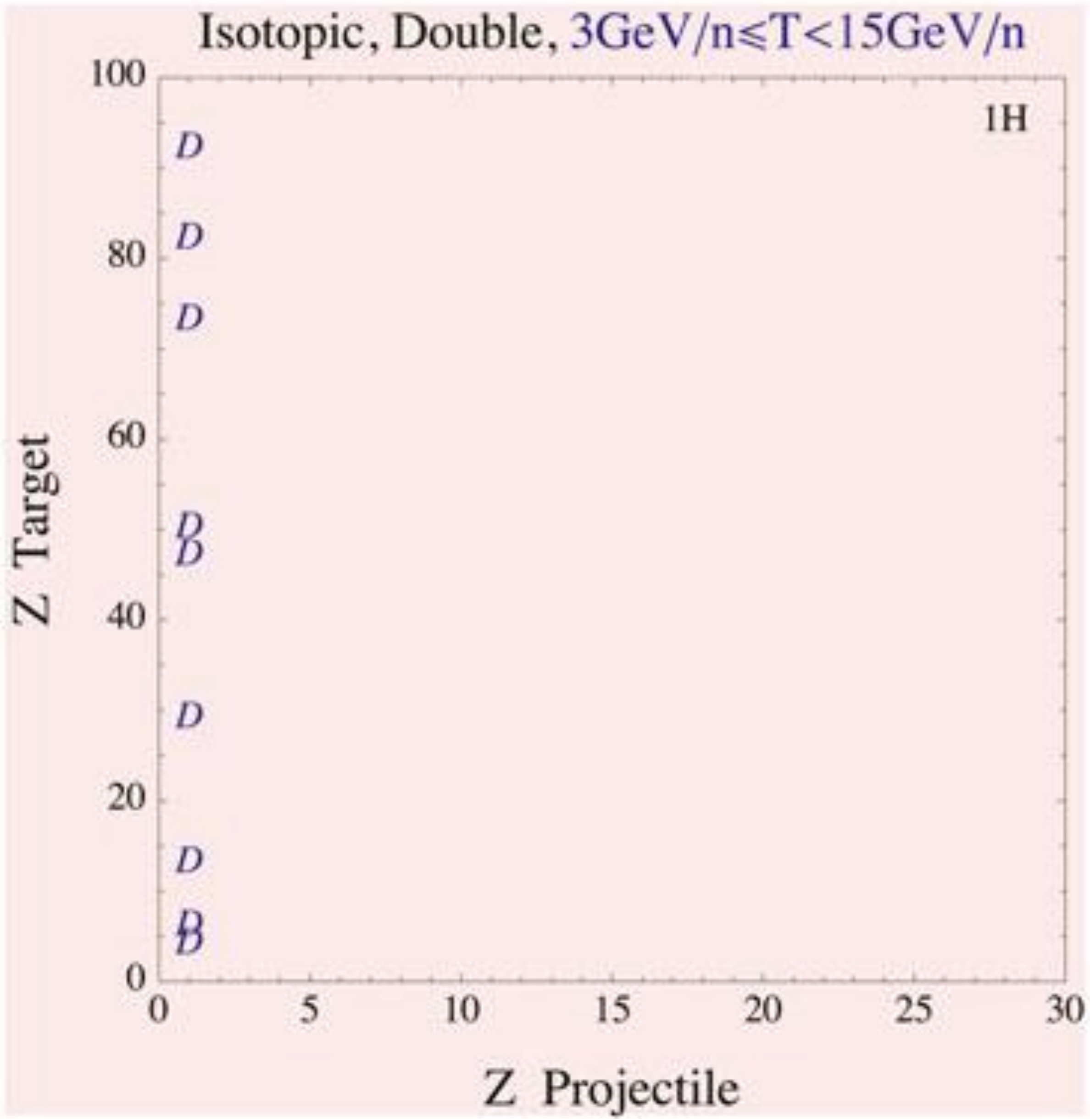
These studies concentrate on light nuclei because they are more penetrating but do not consider light particles like pions and kaons which are more abundant on the GeV scale

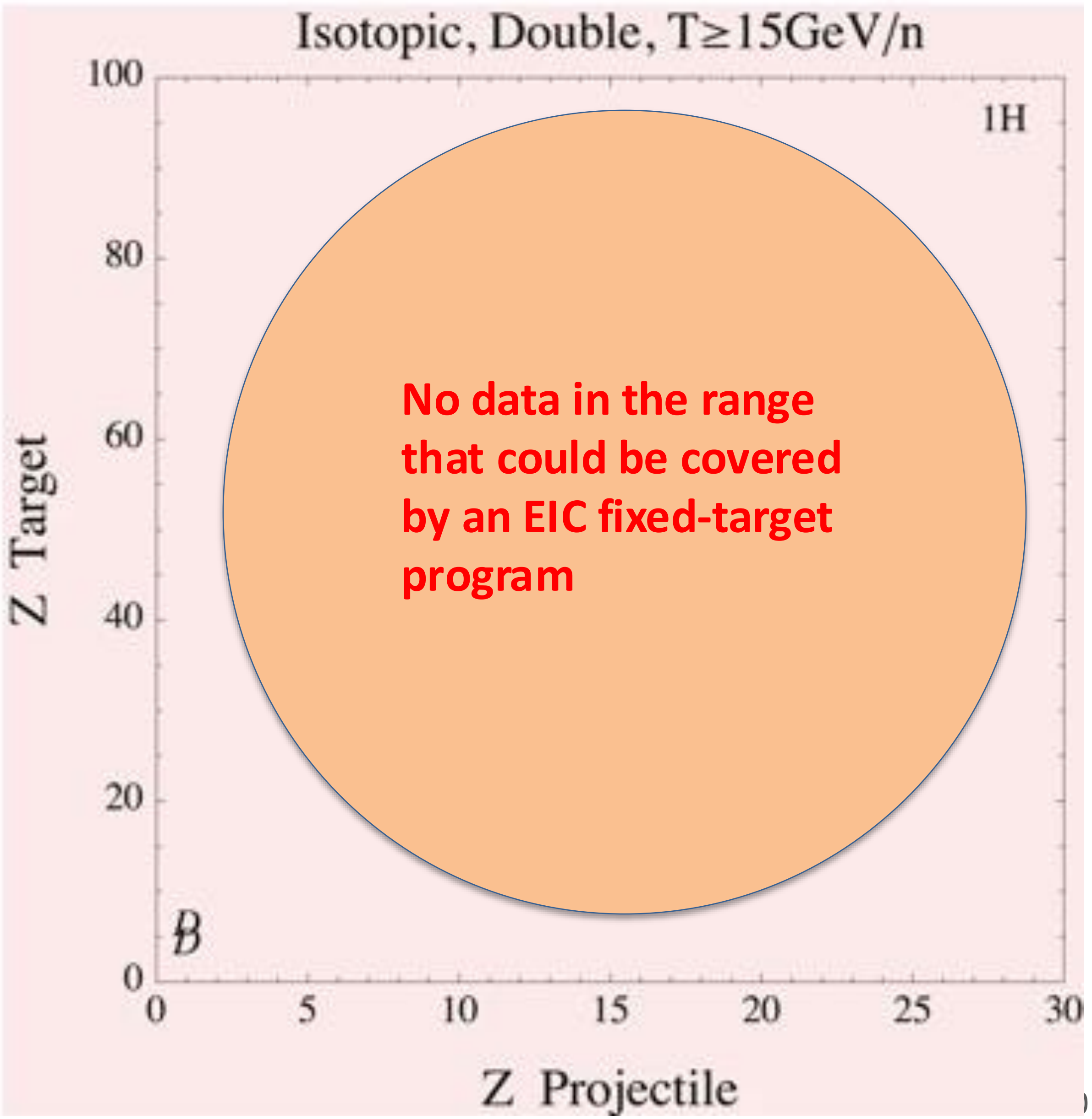
Available data on emitted H ions for T < 3 GeV/n





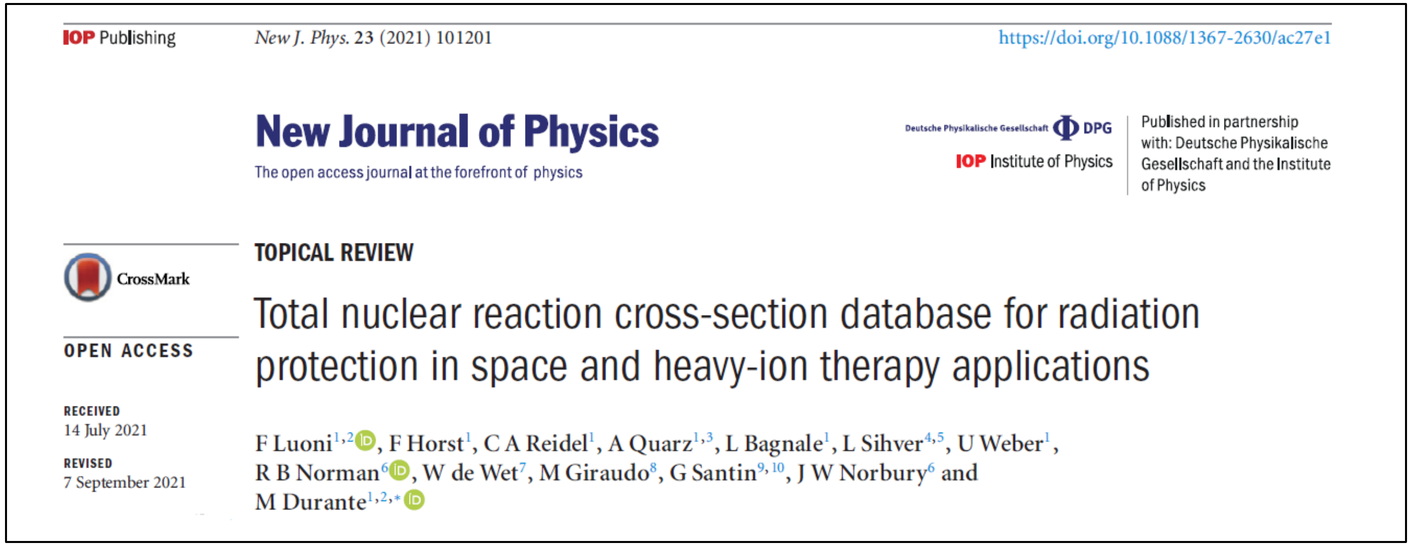
Available data on emitted H ions for T > 3 GeV/n





US nuclear databases do not include charged particle interactions

ESA-GSI-NASA database contains available total reaction cross section data (along with website); working on a similar publication for production cross sections


IOP Publishing New J. Phys. 23 (2021) 101201 https://doi.org/10.1088/1367-2630/ac27e1

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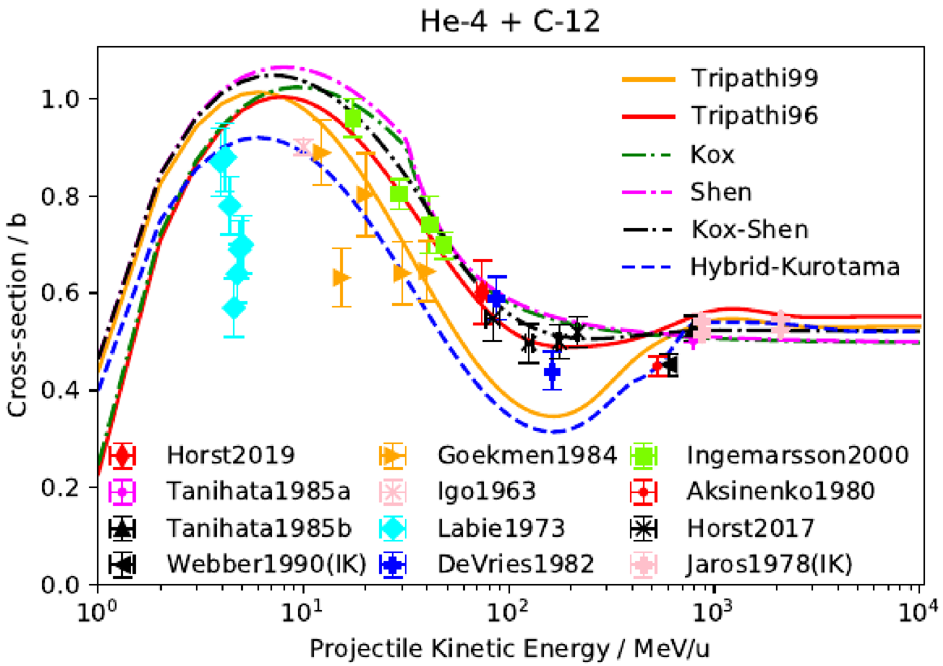
TOPICAL REVIEW

Total nuclear reaction cross-section database for radiation protection in space and heavy-ion therapy applications

F Luoni[1,2], F Horst[1], C A Reidel[1], A Quarz[1,3], L Bagnale[1], L Sihver[4,5], U Weber[1], R B Norman[6], W de Wet[7], M Giraudo[8], G Santin[9,10], J W Norbury[6] and M Durante[1,2,*]

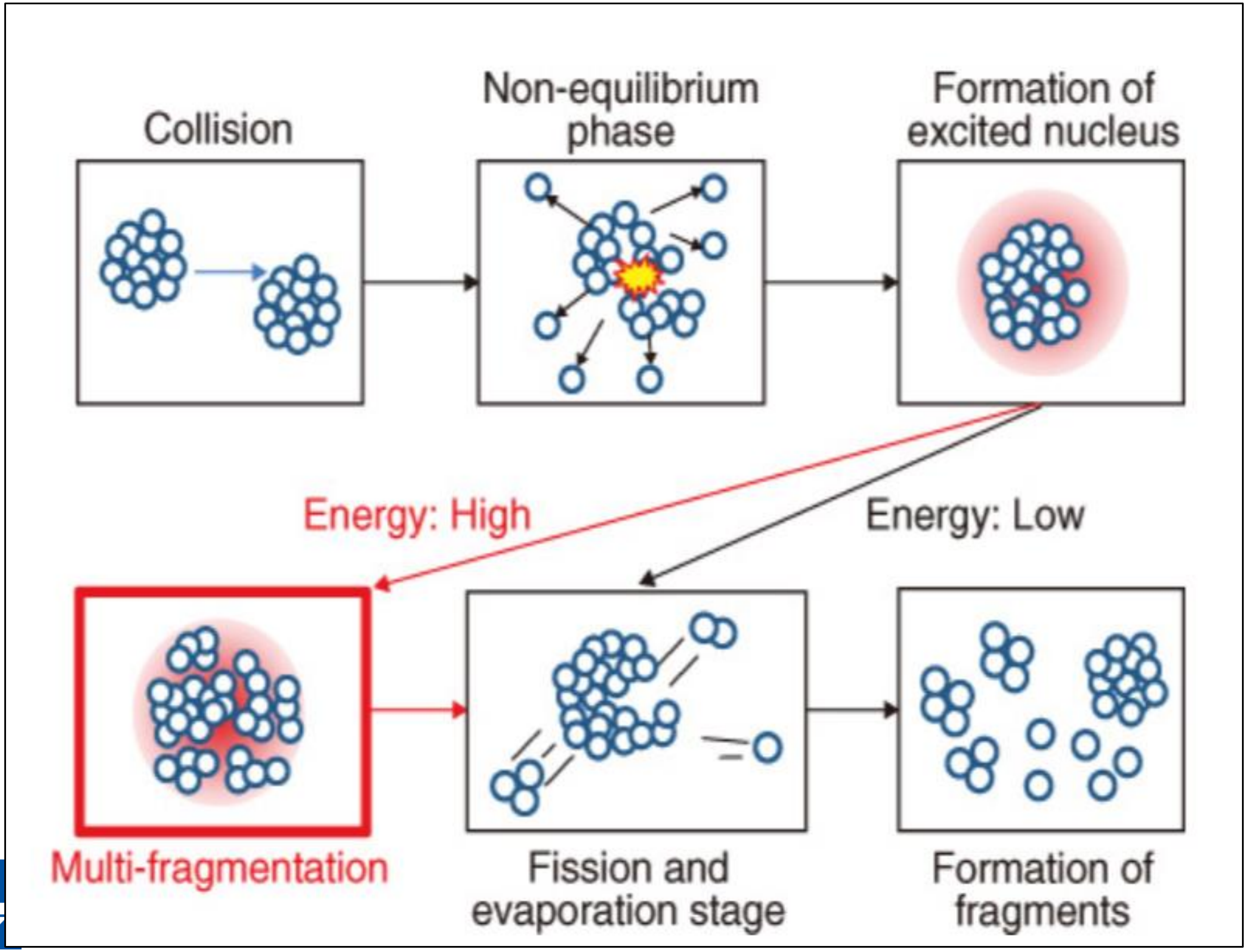
https://www.gsi.de/fragmentation

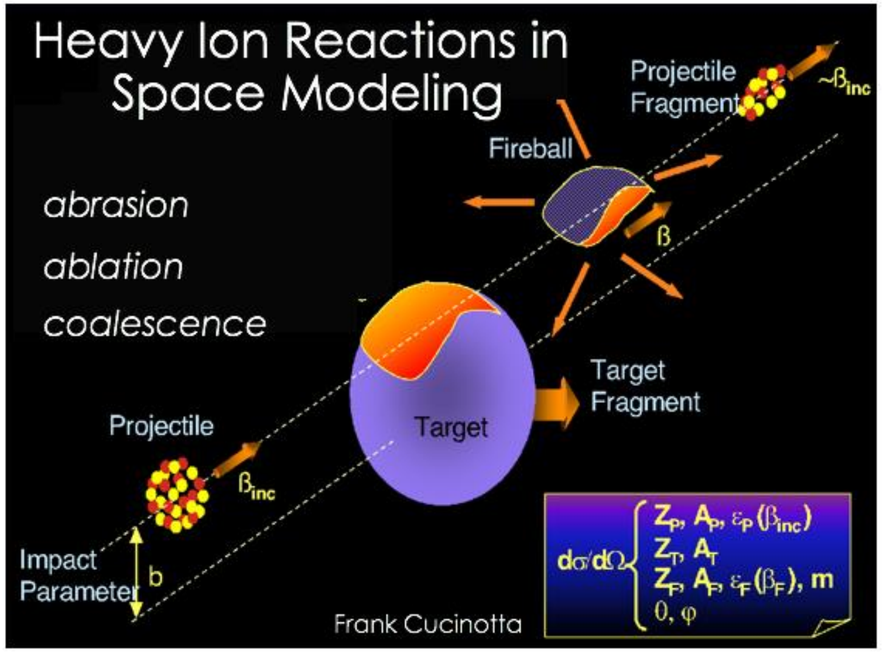
The website also plots cross section parameterizations against the data, plot shown here shows limitations of existing data and models, few data available above 1 GeV and basically none above 3 GeV – data are needed to test models



How are these GCR interactions modeled?

The model strategy depicted below is a bit deceiving: high energy here refers to T ~ 50-100 MeV/n, not applicable to GCRs. Above 1 GeV/n the strong force overwhelms the electromagnetic force and the physics completely changes.





These types of models (abrasion/ablation, *etc*.)
date back to the 1970s, before more sophisticated codes were available

D. Brown, M. Smith

NASA uses very simple phenomenological models

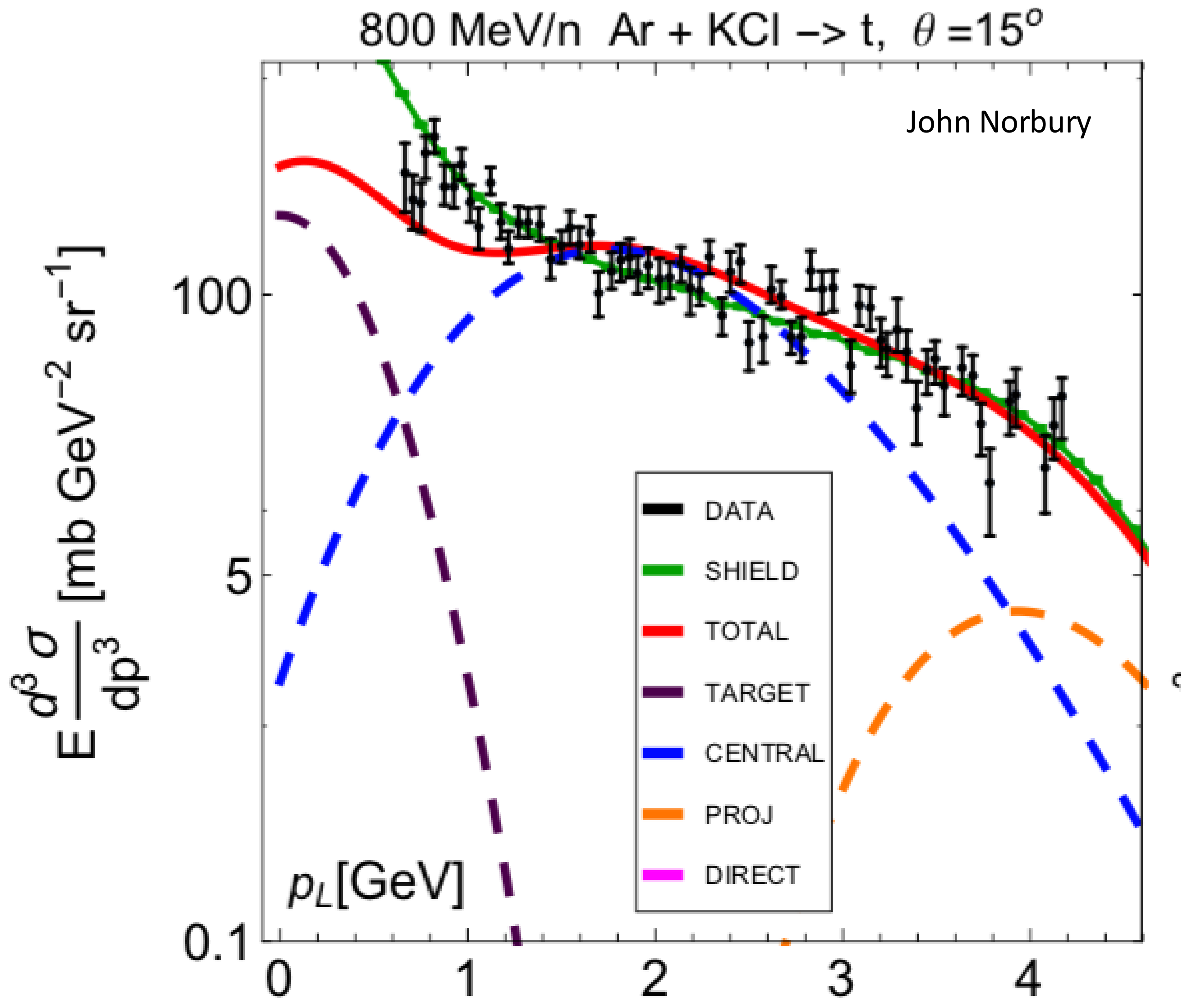
Double differential fragmentation model,
John Norbury, NASA

THERMAL / COALESCENCE MODEL FOR LIGHT ION PRODUCTION

$$
\begin{aligned}
E_A \frac{d^3\sigma_A}{dp_A^3} = \; & C_A N_4^A \Big\{ w_{\mathcal{P}} \exp[(m_{\rm p} - \gamma_{\mathcal{P}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{P}L}\, \beta_{\mathcal{P}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{P}}] \\
& + w_{\mathcal{C}} \exp[(m_{\rm p} - \gamma_{\mathcal{C}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{C}L}\, \beta_{\mathcal{C}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{C}}] \\
& + w_{\mathcal{T}} \exp[(m_{\rm p} - \gamma_{\mathcal{T}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{T}L}\, \beta_{\mathcal{T}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{T}}] \\
& + w_{\mathcal{D}} w_{\mathcal{D}}^{({\rm p})} \exp[(m_{\rm p} - \gamma_{\mathcal{P}L} \sqrt{p_{{\rm p}L}^2 + m_{\rm p}^2} + \gamma_{\mathcal{P}L}\, \beta_{\mathcal{P}L}\, p_{{\rm p}L} \cos\theta_{{\rm p}L})/\Theta_{\mathcal{D}}] \Big\}^A
\end{aligned}
$$

$$
\begin{aligned}
N_4 = \; & \frac{\sigma_{\rm p}}{4\pi m_{\rm p}} \Big[\Theta_{\mathcal{P}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{P}}}}\, K_1\!\left(\frac{m_{\rm p}}{\Theta_{\mathcal{P}}}\right) + \Theta_{\mathcal{C}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{C}}}}\, K_1\!\left(\frac{m_{\rm p}}{\Theta_{\mathcal{C}}}\right) \\
& + \Theta_{\mathcal{T}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{T}}}}\, K_1\!\left(\frac{m_{\rm p}}{\Theta_{\mathcal{T}}}\right) + w_{\mathcal{D}}^{({\rm p})}\, \Theta_{\mathcal{D}}\, e^{\frac{m_{\rm p}}{\Theta_{\mathcal{D}}}}\, K_1\!\left(\frac{m_{\rm p}}{\Theta_{\mathcal{D}}}\right) \Big]^{-1}
\end{aligned}
$$

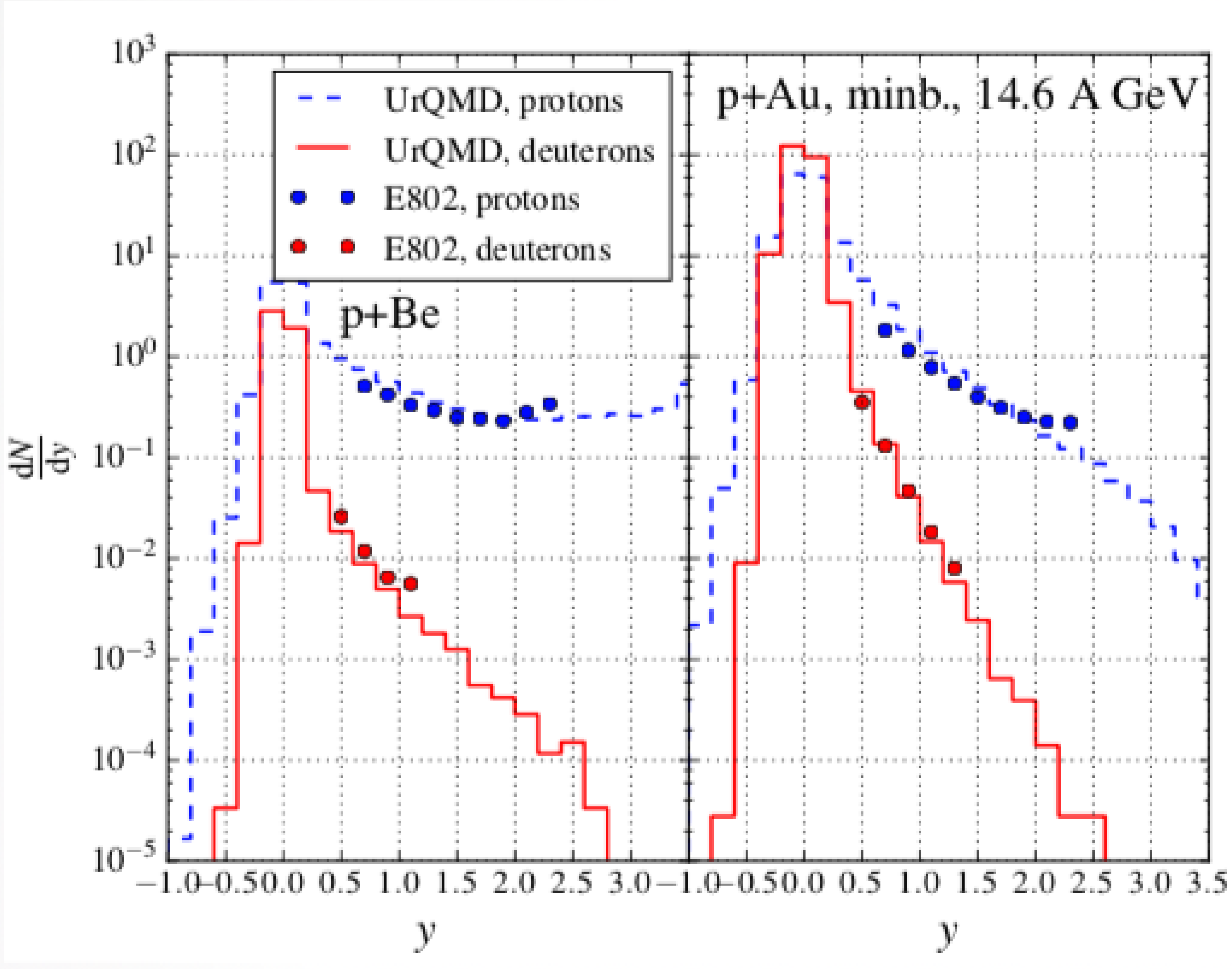
Sum of 4 exponentials
15 parameters, doesn't cover final-state emission of anything but protons and light ions



M. Smith

Interactions are ideal for heavy-ion transport models

Marcus Bleicher, UrQMD (2018)



Reaction modeling for space applications could benefit from interactions with heavy-ion physicists

Existing transport models for intermediate and high-energy reactions can be directly applied to space physics without significant change

Current heavy-ion transport models are far beyond NASA standards

Type of model required depends on energy

For GCR energies up to a GeV or so, multifragmentation-type models, with particle production are likely most applicable (BUU, VUU, QMD), hadronic matter only

At higher energies, codes including more particles or phase transitions may be better suited, e.g. UrQMD, HSD and others

Event-by-event transport models that follow all particles would be a huge advance over what is currently available and can be directly applied to the problem

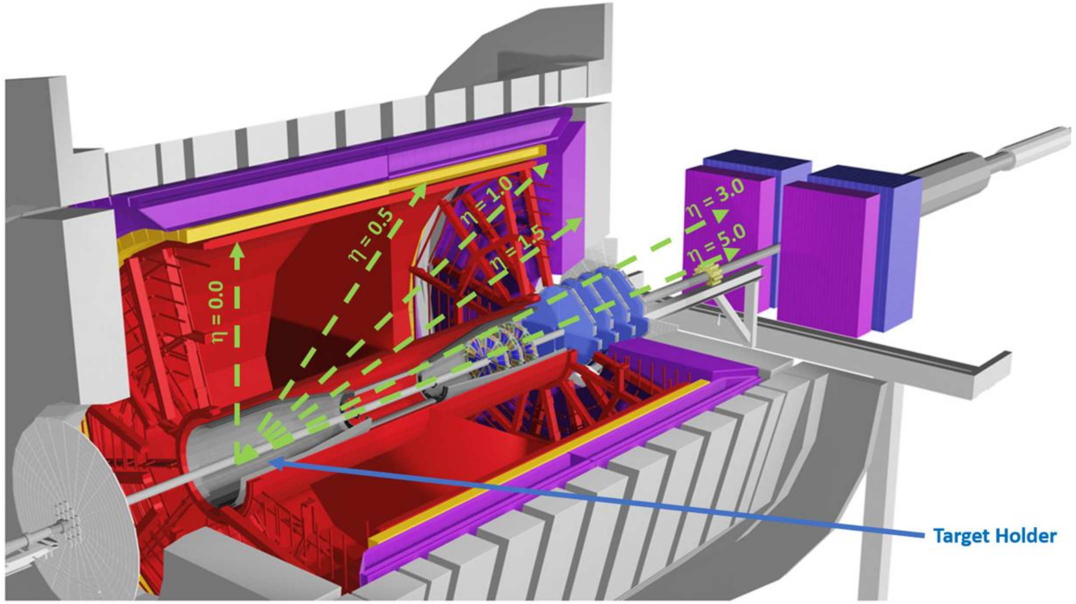
Greatest interest is in double differential distributions: spectra at different angles

This type of application falls under the umbrella of “nuclear data”

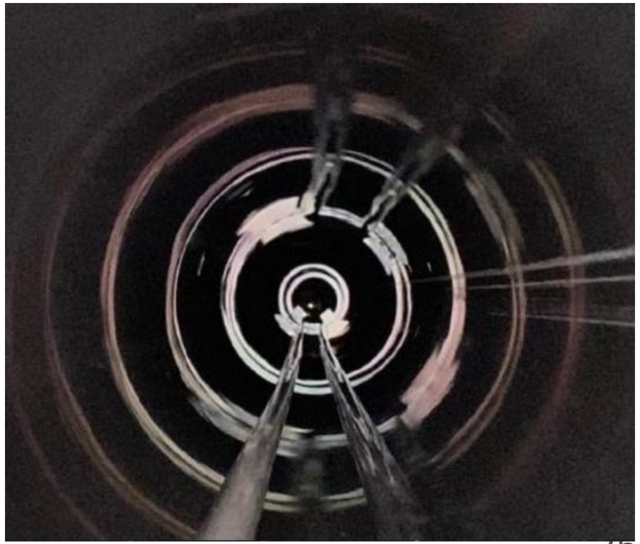
Some of These Missing Data Could be Obtained by STAR

2023-2025 Beam Use Request:
light fragment yields from C, Al, and Fe on C, Al, and Ni targets
with beam energies from 5 to 50 GeV

FXT Energy $\sqrt{s_{NN}}$(GeV)	Single Beam E_T (GeV)	Single beam E_k (A/GeV)	y_{cm}	Chem. Pot. μ_B (MeV)	Year
3.0	3.85	**2.9**	1.05	721	2018
3.2	4.59	**3.6**	1.13	699	2019
3.5	5.75	**4.8**	1.25	666	2020
3.9	7.3	**6.3**	1.37	633	2020
4.5	9.8	**8.9**	1.52	589	2020
5.2	13.5	**12.6**	1.68	541	2020
6.2	19.5	**18.6**	1.87	487	2020
7.2	26.5	**25.6**	2.02	443	2018
7.7	31.2	**30.3**	2.10	420	2020
9.1	44.5	**43.6**	2.28	372	2021
11.5	70	**69.1**	2.51	316	2021
13.7	100	**99.1**	2.69	276	2021

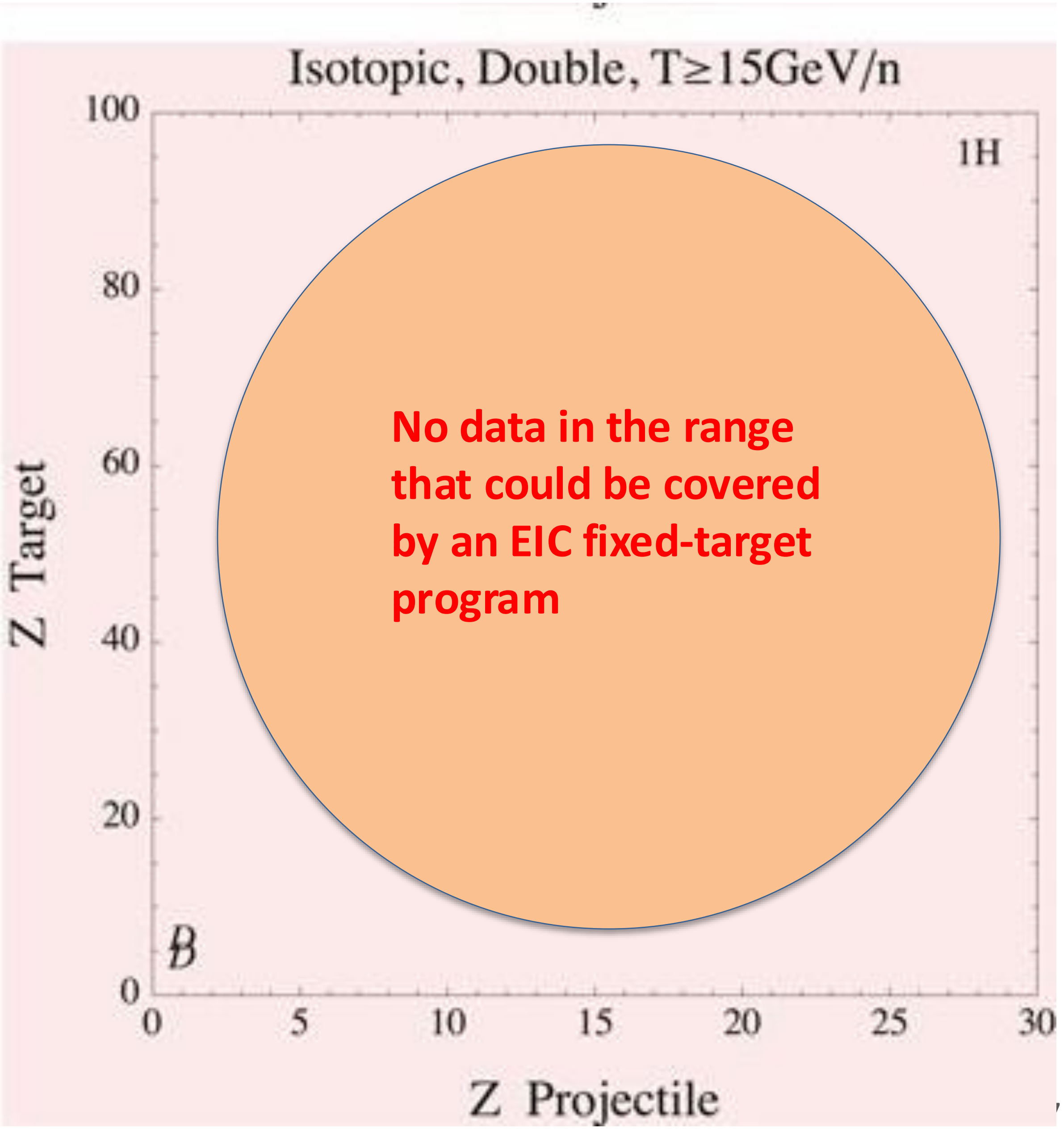


STAR has been run in fixed-target mode from 2018-2021 for Au+Au collisions (BES II)



Fixed-target programs can help fill the data and modeling gap

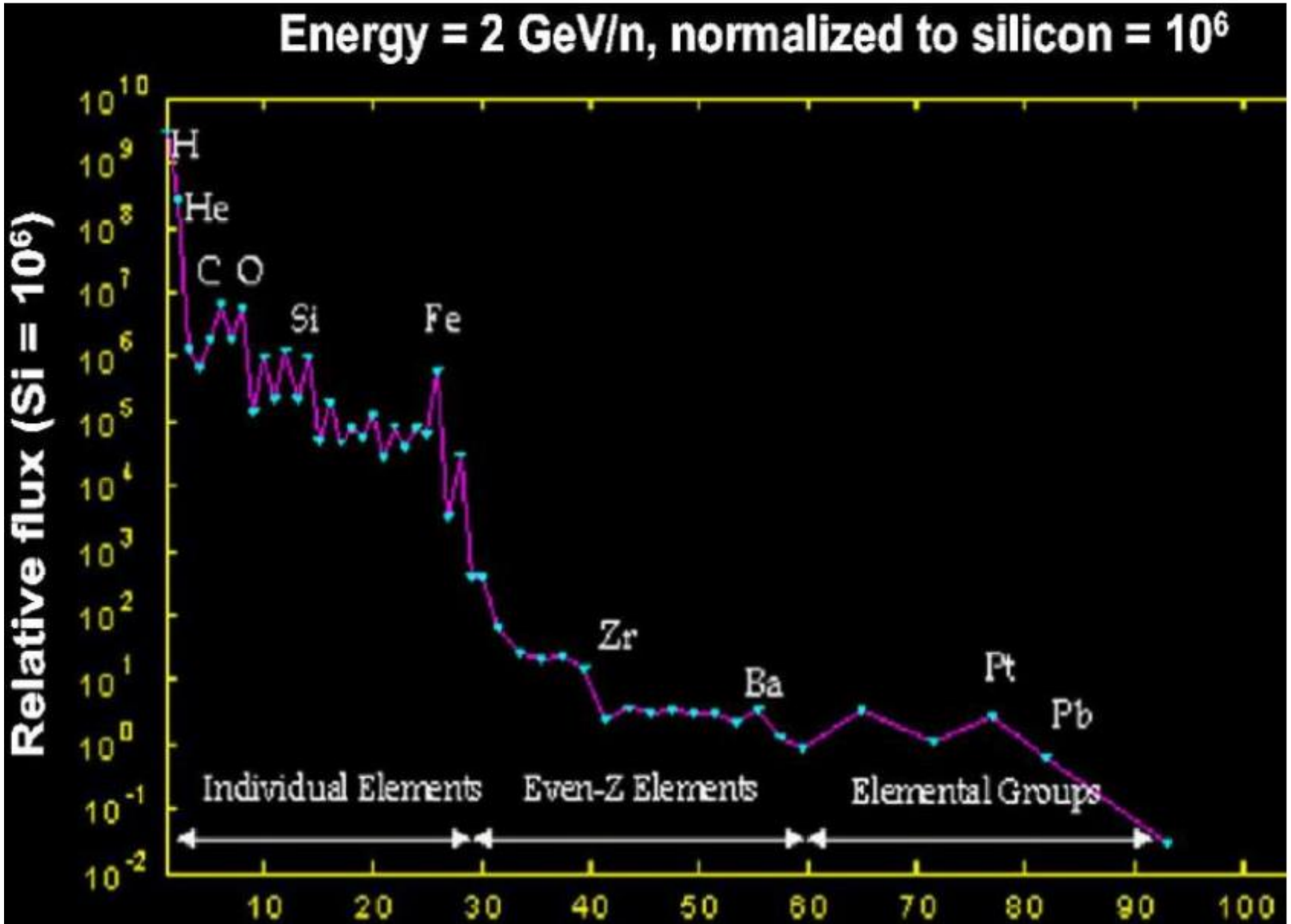
- CNFS Ad Hoc Meeting July 2025: New Horizons with Fixed-Target Proton-Nucleus Experiments at Intermediate Energies
  - AGS top energy is 10 GeV/n
  - Already used by NASA's Space Radiation Lab at BNL
- FAIR at GSI is in same energy range as AGS
- EIC fixed-target program at top energy of 100 GeV could fill in the blank space in the high energy range required for GCRs
- Only CERN SPS goes to higher energy
- These studies could fill an urgent need for nuclear data and modeling for space while advancing heavy-ion physics at the same time



Thank you!

How Does This Community Fit Into Space Applications?

- Galactic cosmic rays (GCRs) – protons and ions up to TeV energies – interact with anything in their path like spacecrafts and astronauts and can cause damage
- These interactions create a cascade of secondaries that can do further damage and have been studied for years
- Now that NASA is planning to revive space travel, there is a new focus on the problems that may be encountered over longer missions and it is clear that there are a lot of things that are not well understood and that more work is needed
- This work includes:
  - More data at higher energies to fill gaping holes in information
  - Better modeling – like hadron transport applied to these systems – to replace or augment the primitive ones in use now
- This talk will introduce the problem and point to a new opportunity for transport models


Energy = 2 GeV/n, normalized to silicon = 10^6
Relative flux (Si = 10^6)
H
He
C O
Si
Fe
Zr
Ba
Pt
Pb
Individual Elements
Even-Z Elements
Elemental Groups
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10
20
30
40
50
60
70
80
90
100