Cosmic applications of hadron transport

Ramona Vogt (LLNL/UC Davis)

LLNL-PRES-840137

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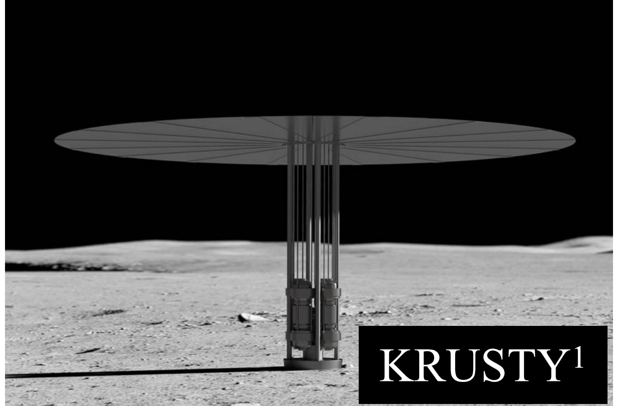
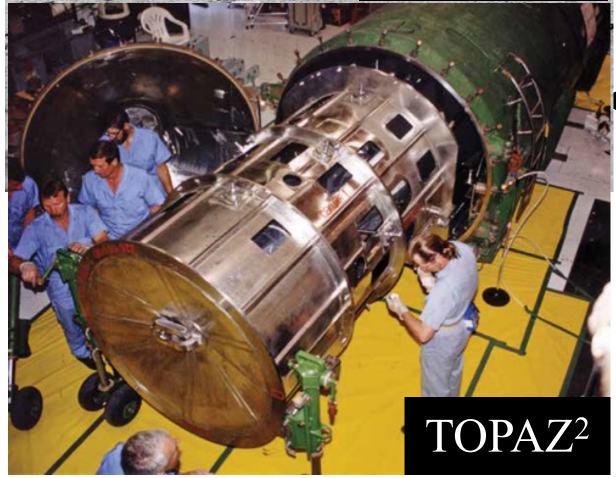
Space Missions Need (High Energy) Data & Transport Modeling

Energy Production





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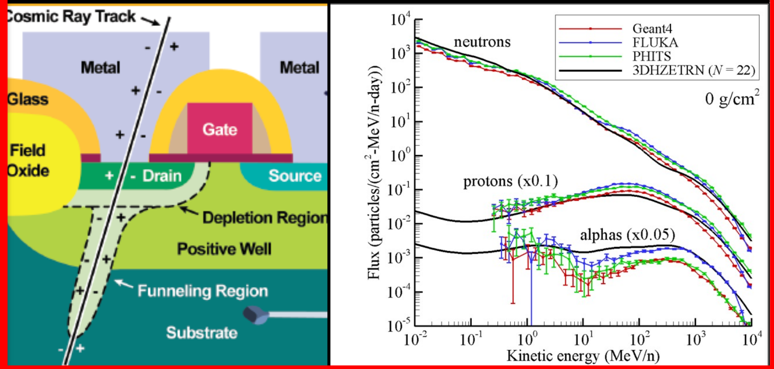
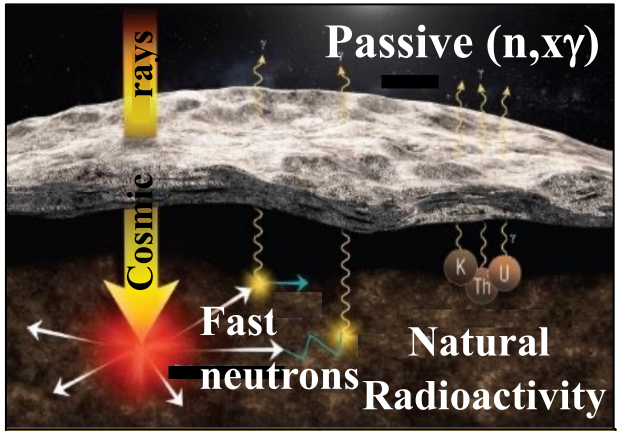
Dose/Shielding Calculations for Electronics and Humans



Data & Transport

Planetary Exploration



Nuclear Propulsion

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

What are the energy ranges of cosmic rays?

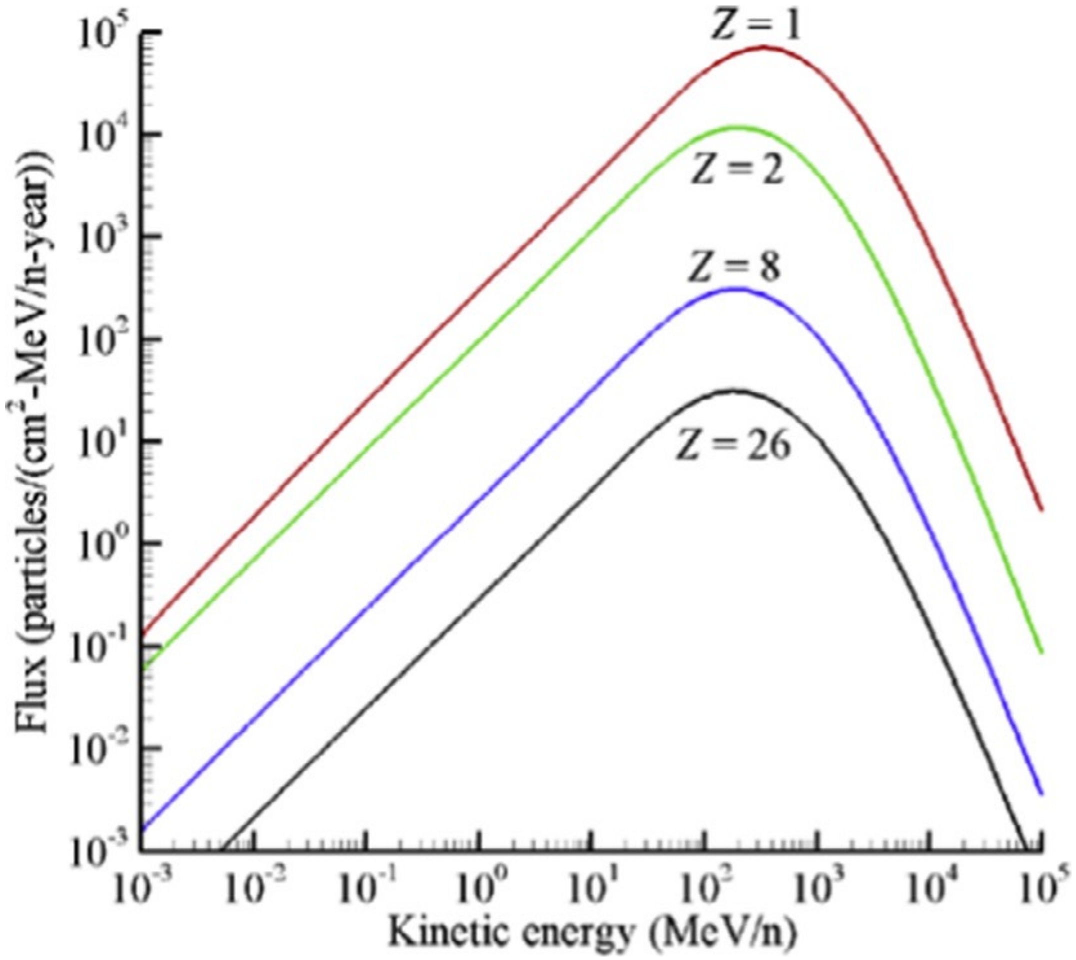
Galactic cosmic rays include everything from protons to heavy nuclei (up to ^{56}Fe) with KE up to 50 GeV/A: peak flux ~ 100 MeV - 1 GeV

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



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

What do these secondaries look like?

When a cosmic ray strikes the atmosphere, or rather a nucleus like nitrogen or oxygen 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 (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

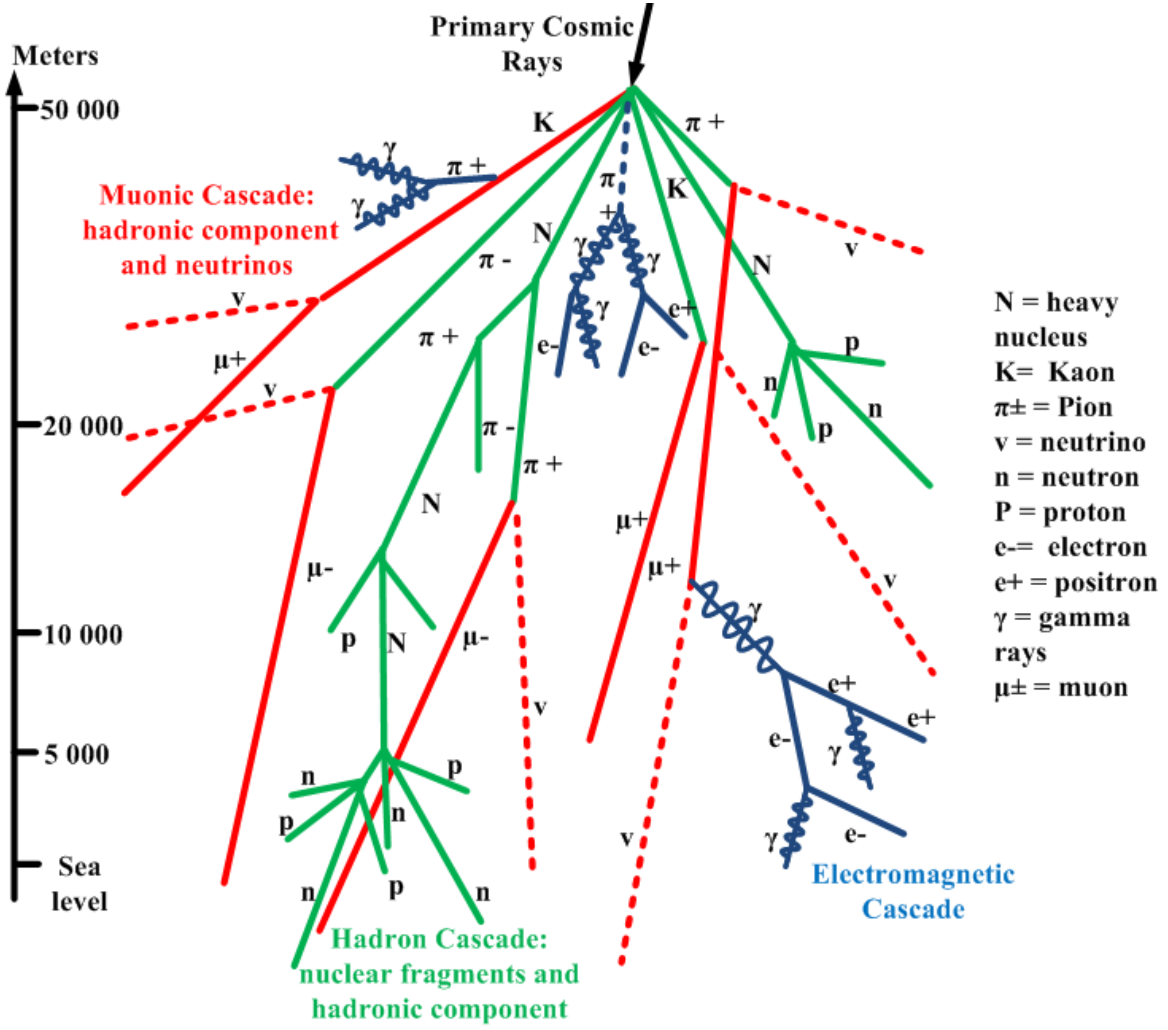
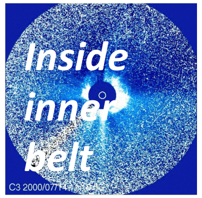


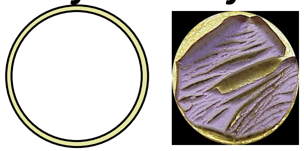
Diagram by Daniel Gomez Toro

What can go wrong? (near-Earth environment)

False stars in star tracker CCDs

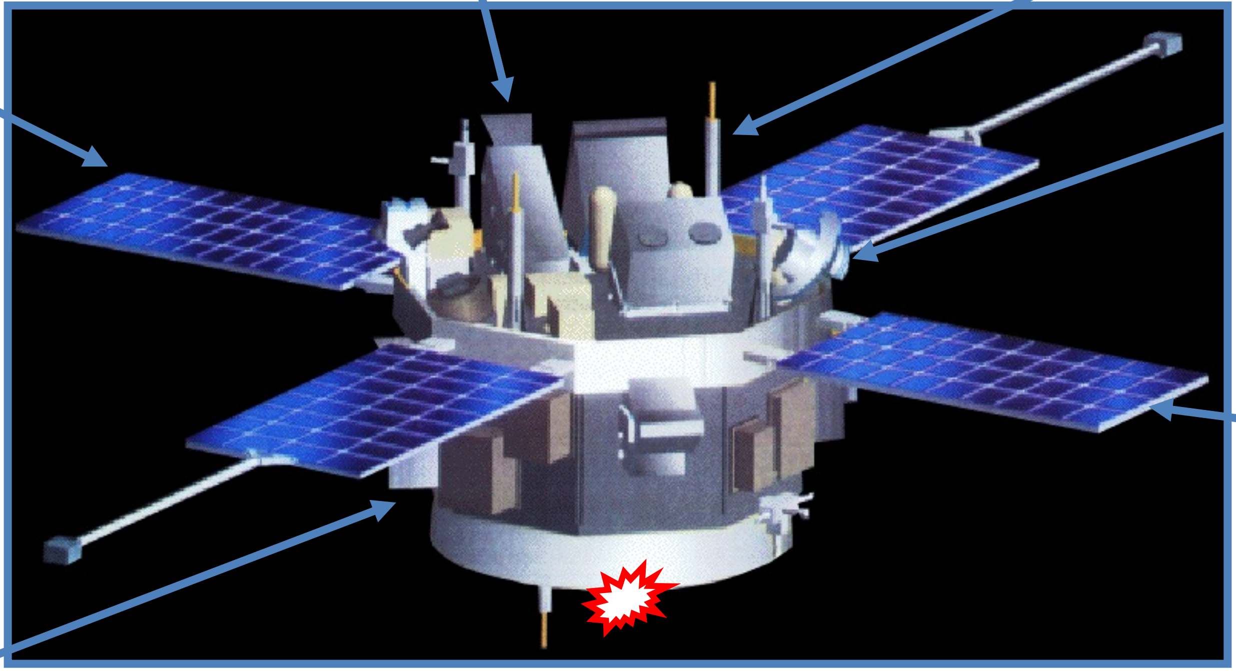


before ***after***



Surface degradation from radiation

Solar array power decrease due to radiation damage

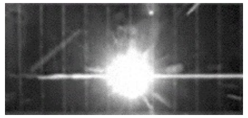


Electronics degrade due to total radiation dose

Single event effects in microelectronics

1101 => 0101

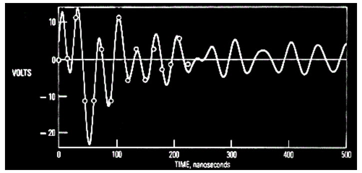
Solar array arc discharge



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

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*.

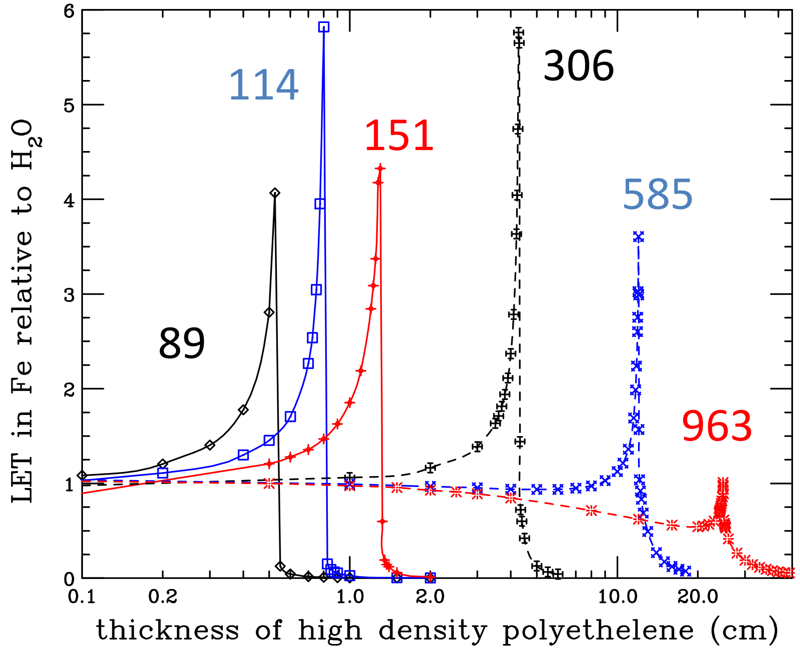
As $E \rightarrow 0$, the stopping power increases, leading to a *Bragg Peak* where the highest dose is deposited

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

Higher-energy ions have longer ranges, requiring more material to stop them

Need to balance the shielding needed against damage and dose

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



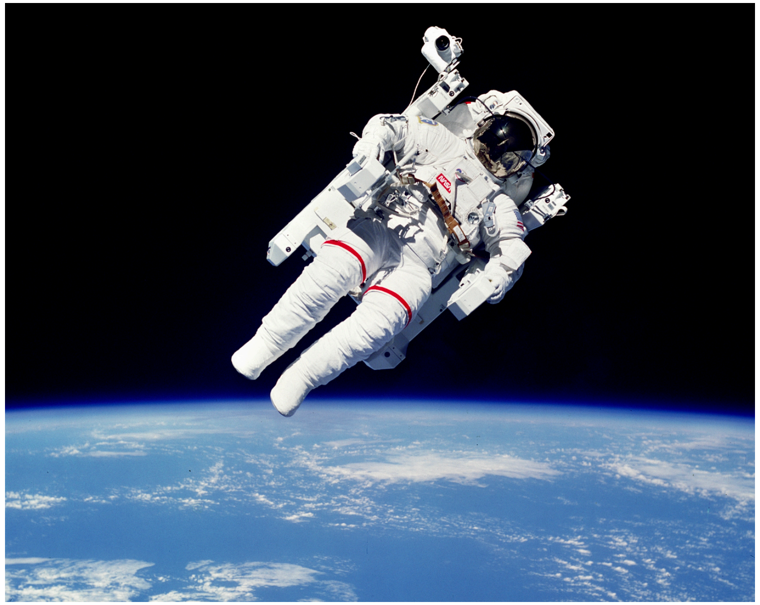
Determining radiation effects on humans (Dose)

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

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

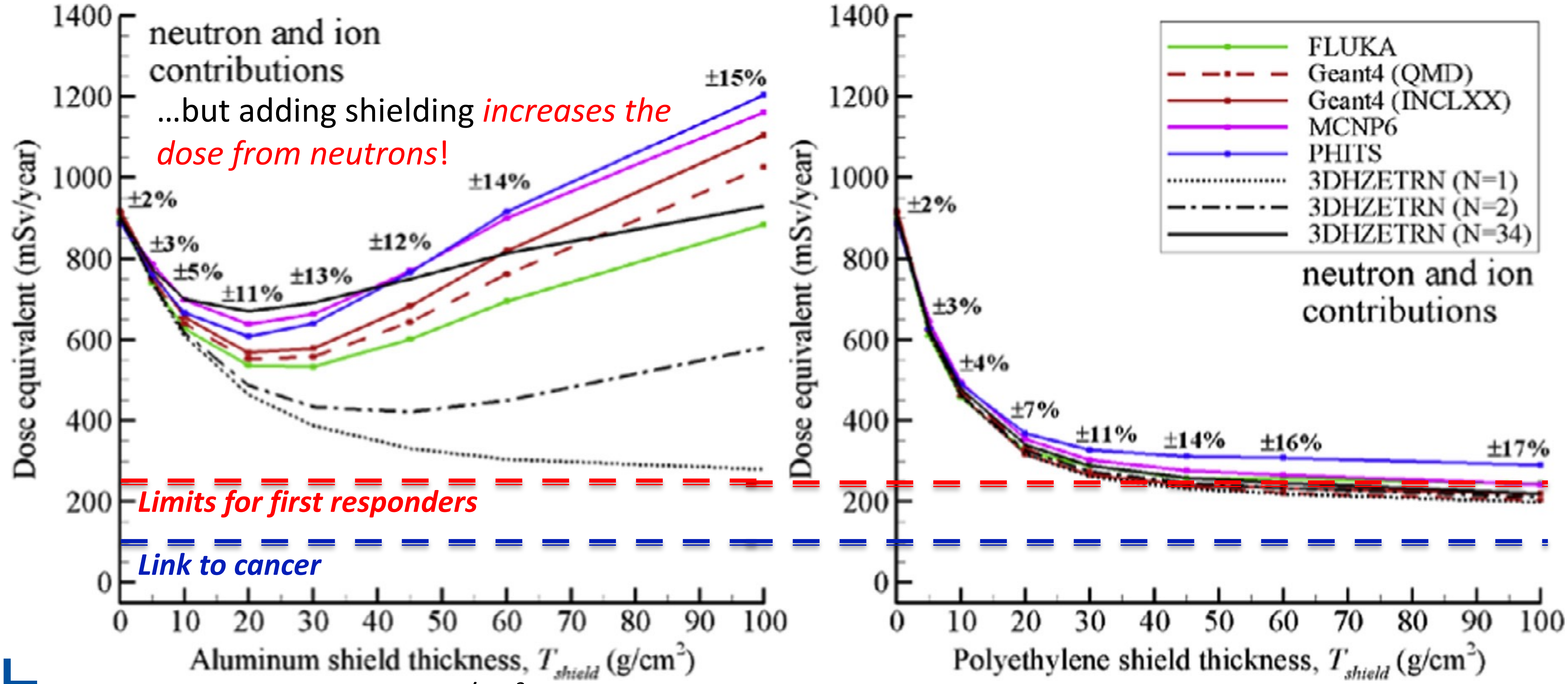
$$\text{Q}_{\gamma-\text{rays}} = 1, \text{Q}_{\alpha} = 20$$

- 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**



Shielding for neutrons and ions

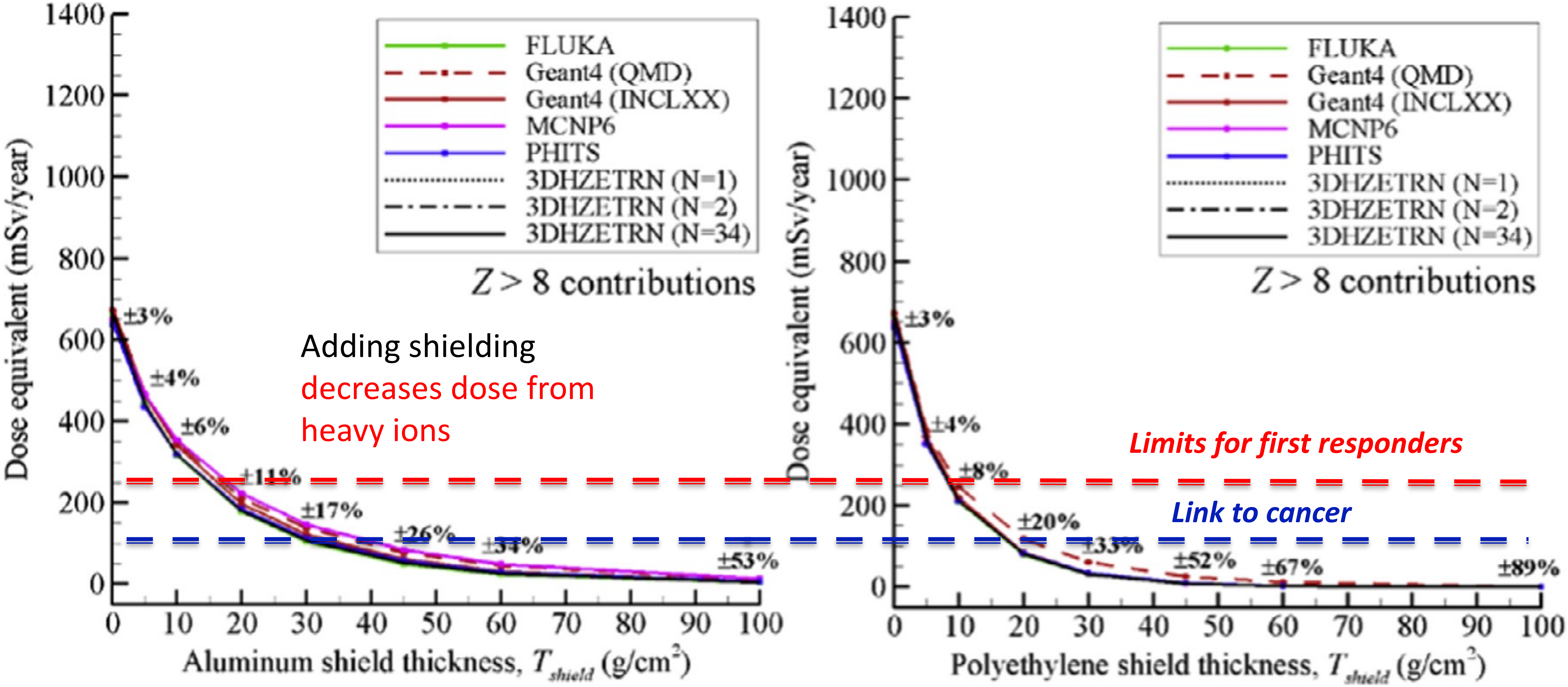
"Variation in model results… is mainly a result of differing nuclear reaction and fragmentation cross sections, affecting both primary and secondary ion transport", Slaba *et al*, Life Sciences in Space Research **12** (2017) 1-15



ρ_{Al}=2.7 g/cm^3

ρ_{PE}=0.97 g/cm^3

Shielding for ions (Z > 8)



Adding shielding decreases dose from heavy ions

Limits for first responders

Link to cancer

ρ_{Al}=2.7 g/cm^3

ρ_{PE}=0.97 g/cm^3

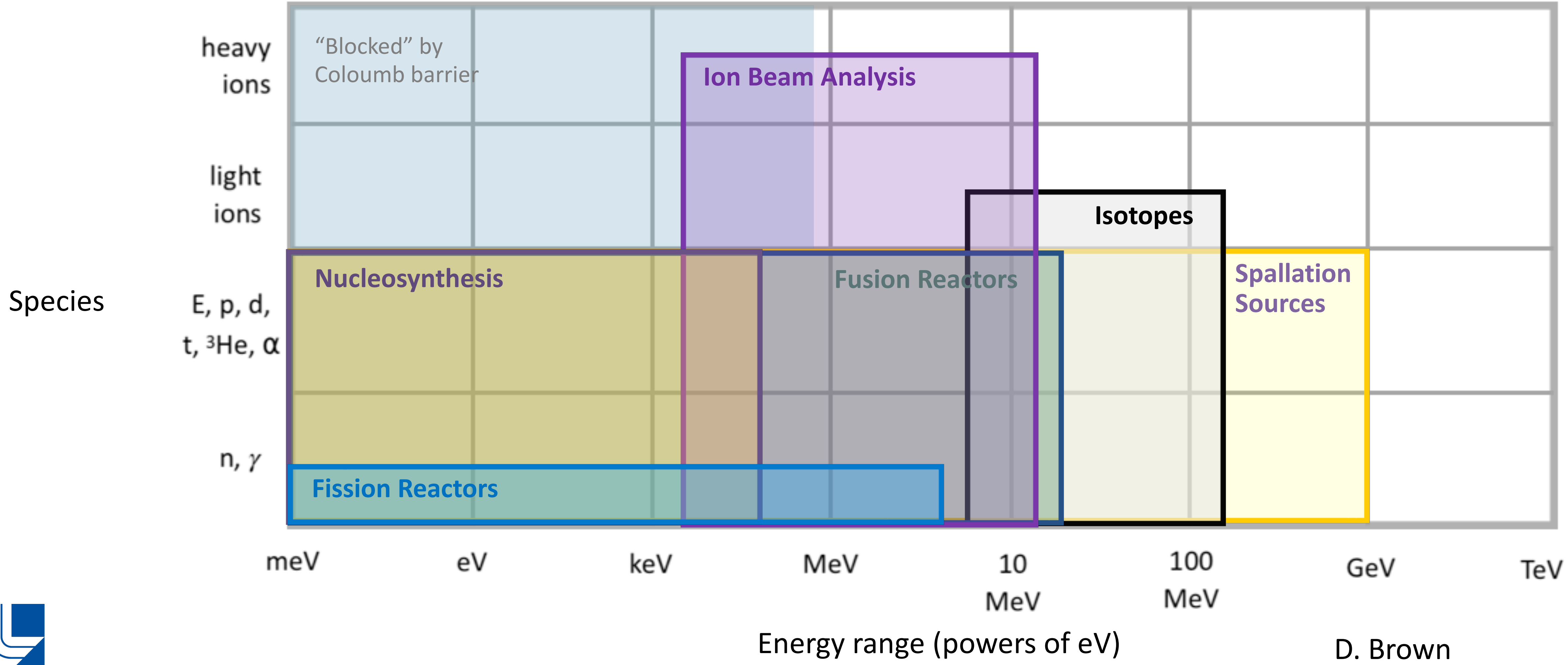
T.C. Slaba et al. Life Sciences in Space Research **12** (2017) 1–15

L. Bernstein

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

Typical databases in the US do not include p or ion 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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7 September 2021

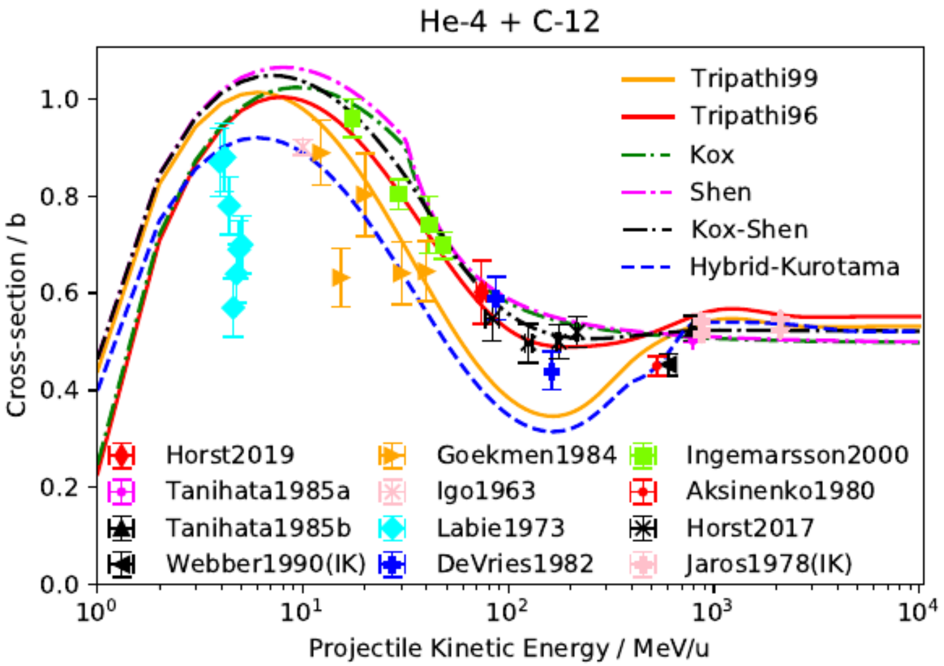
TOPICAL REVIEW

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

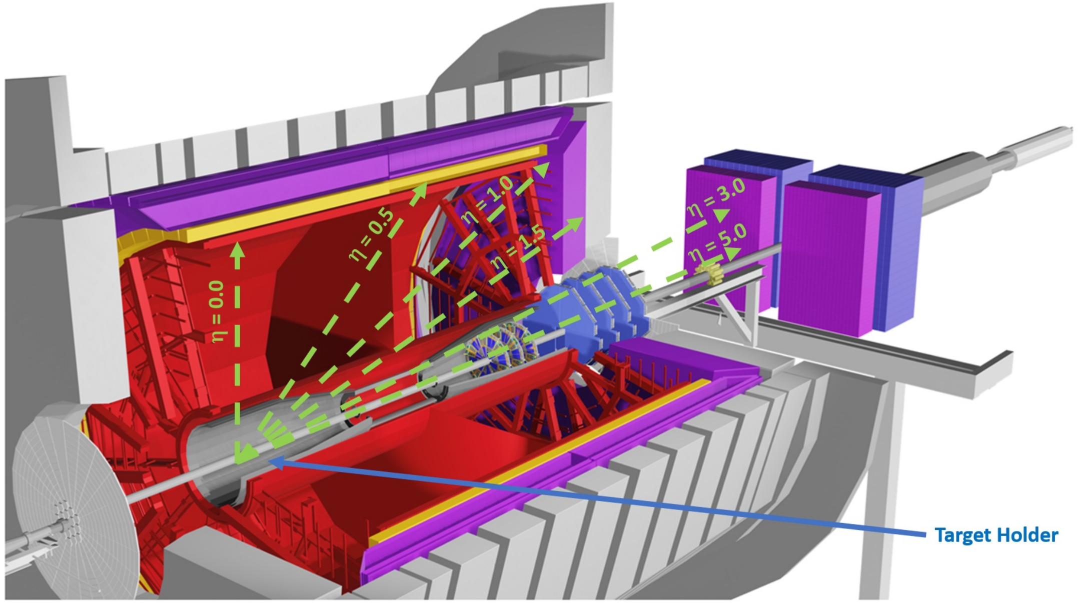
The website also plots cross section parameterizations against the data, plot shown here shows limitations of existing data and models, few data available above 1 GeV and basically none above 3 GeV – data are needed to test models



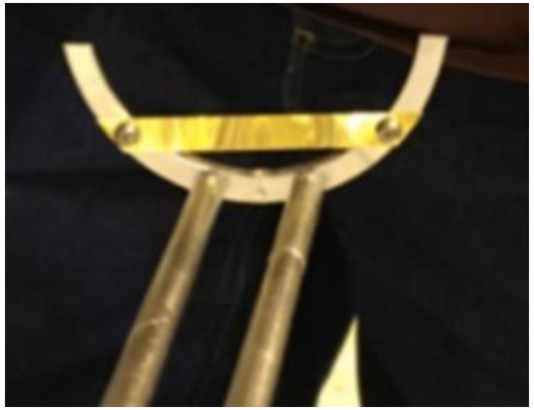
Some of These Missing Data Could be Obtained by STAR

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

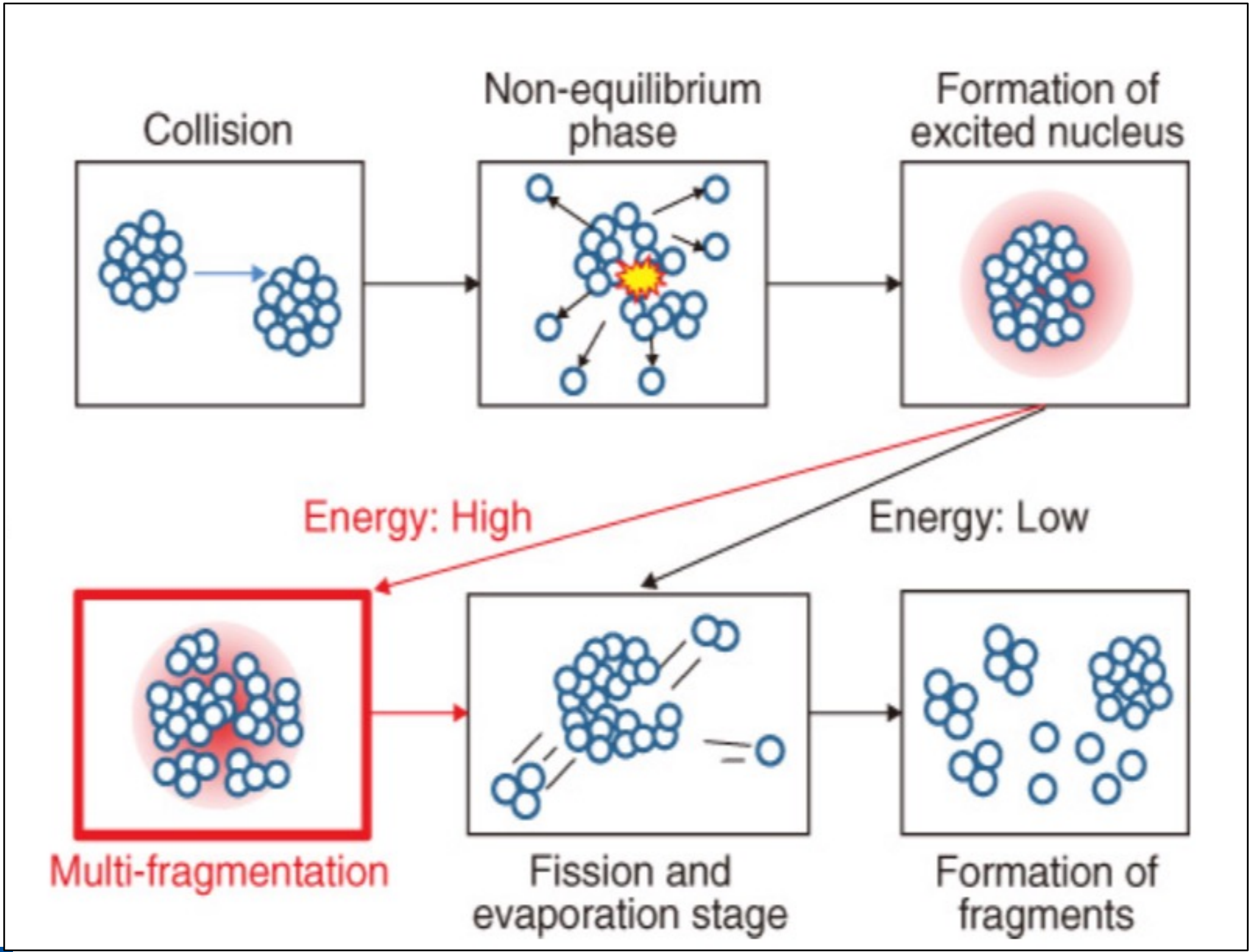
FXT Energy $\sqrt{s_{NN}}$(GeV)	Single Beam E_T (GeV)	Single beam E_k (A/GeV)	y_{cm}	Chem. Pot. μ_B (MeV)	Year
3.0	3.85	**2.9**	1.05	721	2018
3.2	4.59	**3.6**	1.13	699	2019
3.5	5.75	**4.8**	1.25	666	2020
3.9	7.3	**6.3**	1.37	633	2020
4.5	9.8	**8.9**	1.52	589	2020
5.2	13.5	**12.6**	1.68	541	2020
6.2	19.5	**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

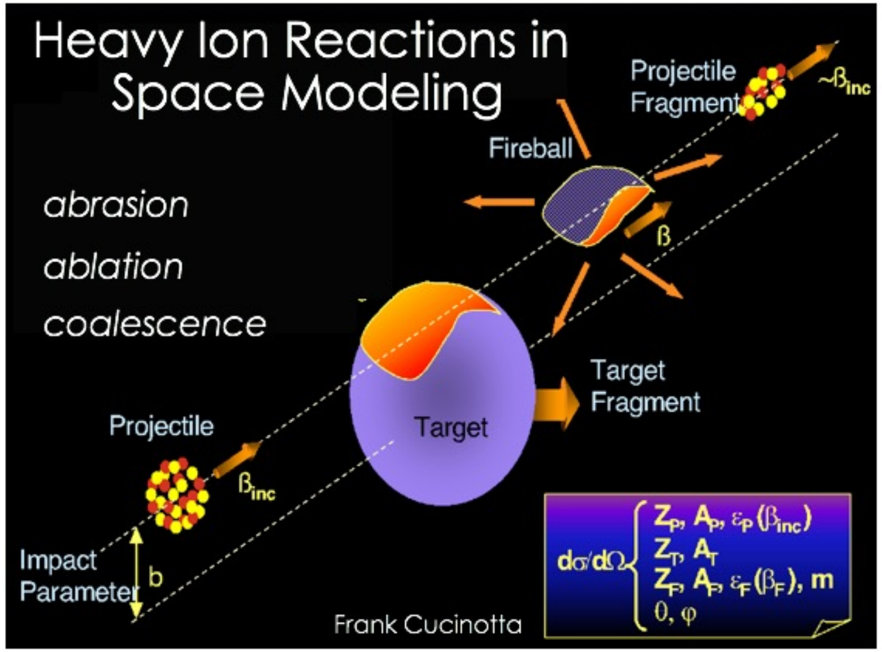


STAR has been run in fixed-target mode from 2018-2021 for Au+Au collisions (BES II)



How are these GCR interactions modeled?





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

NASA uses very simple phenomenological models

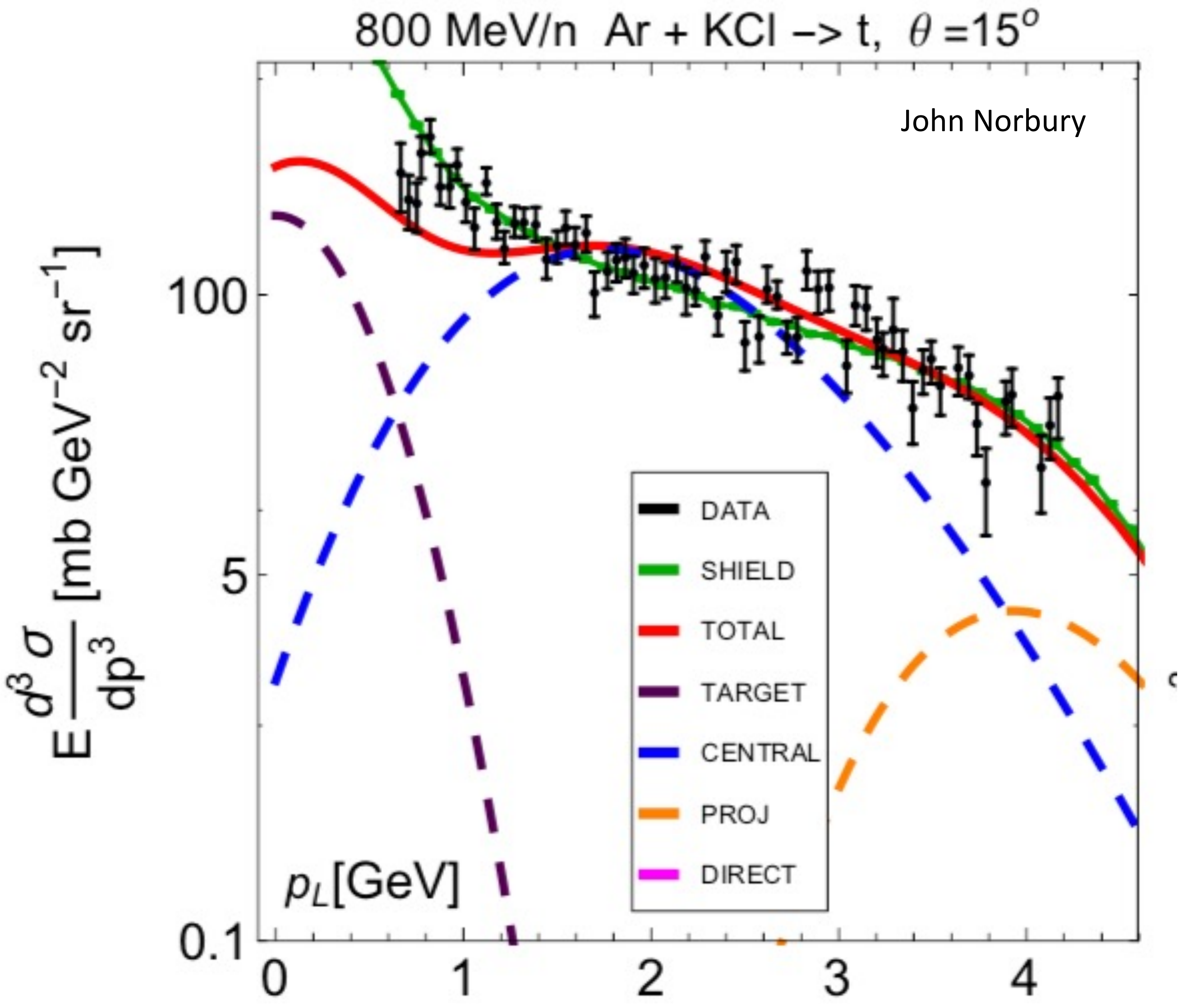
Double differential fragmentation model,
John Norbury, NASA

THERMAL / COALESCENCE MODEL FOR LIGHT ION PRODUCTION

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

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

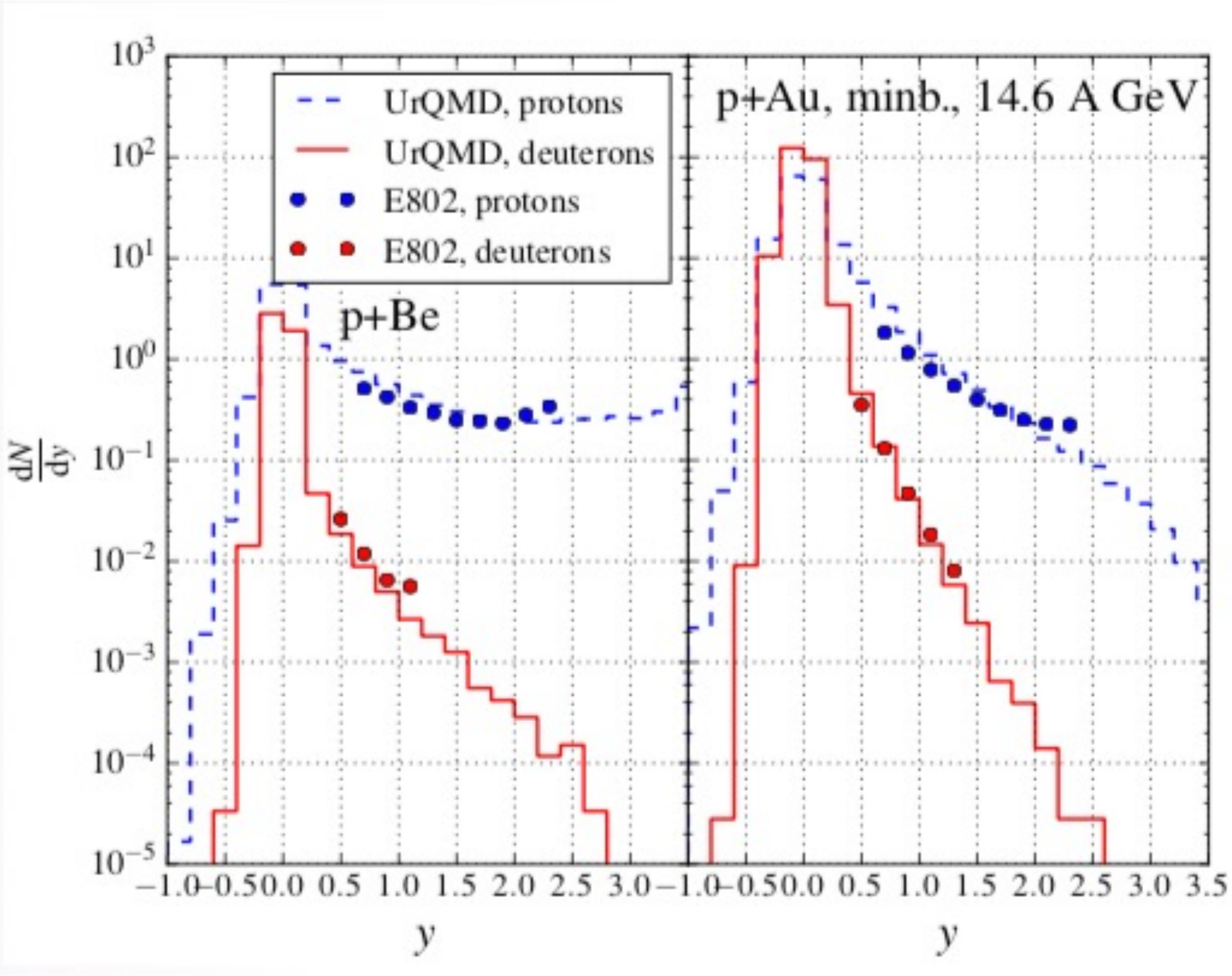
Sum of 4 exponentials
15 parameters, doesn't cover final-state emission
of anything but protons and light ions



M. Smith

These interactions are ideal for hadron transport modeling

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

M. Smith

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

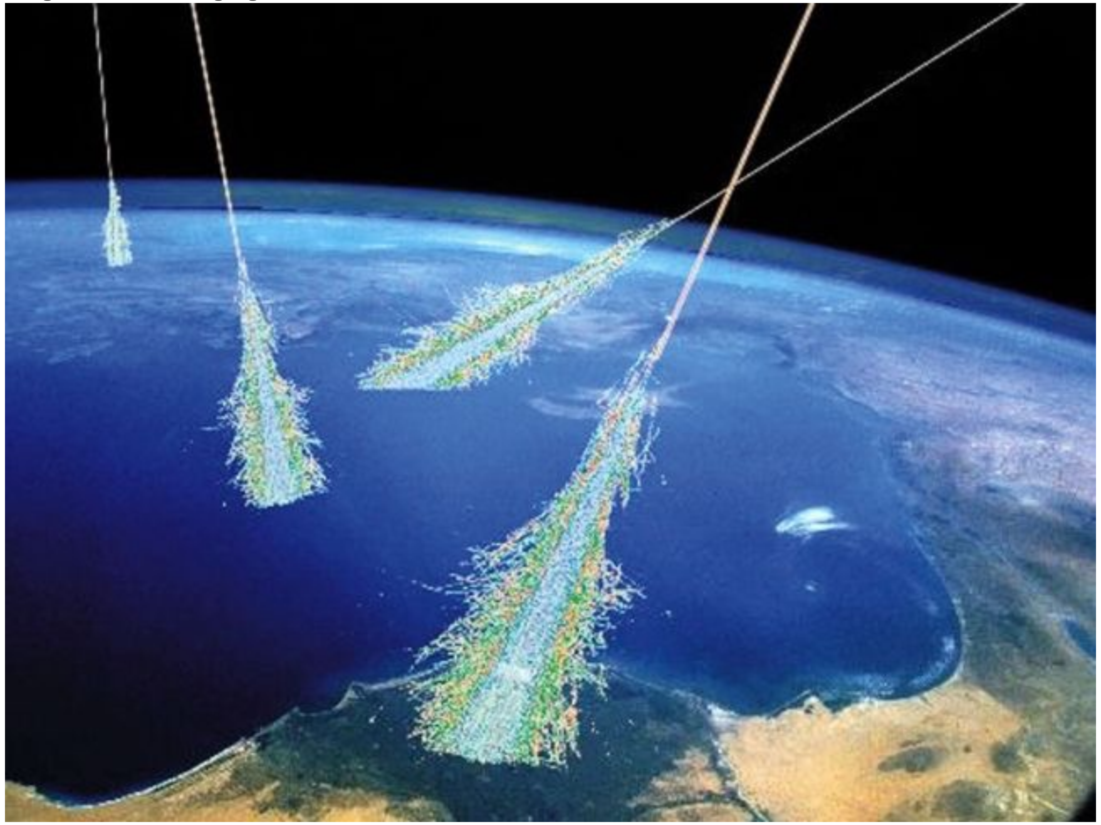
Event-by-event transport models that follow all particles would be a huge advance over what is currently available and can be directly applied to the problem

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

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

Assessment of nuclear data needs: A meeting called WANDA

- Annual assessment of nuclear data needs for applications
- Last 2 meetings have had a major focus on space related applications which also play a role in applications on Earth, especially medical applications like particle therapy
- One focus in 2022 was **high energy data for space applications**



- We are shielded from GCRs on Earth by Earth's magnetic field and atmosphere
- Away from Earth, atmospheric shielding is absent and GCRs can cause damage
- WANDA 2022 showed that there are significant gaps in data and models

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 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

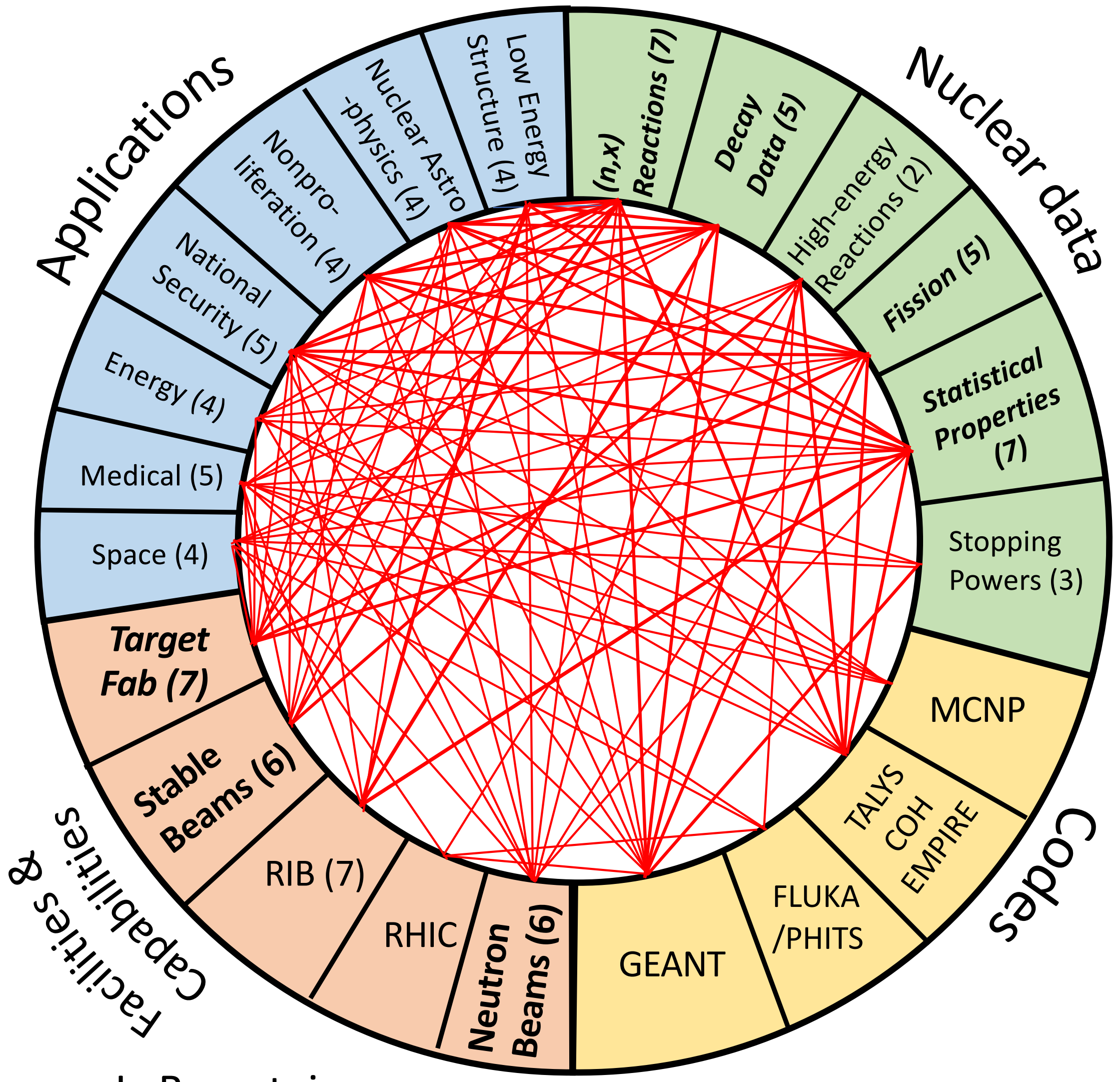


Diagram by A. Spyrou, L. Bernstein

Why are we concerned about nuclear data now?

NSAC charge for nuclear data: April 2022
2 reports expected --
1st at the end of September 2021
on USNDP status;
2nd at the end of January 2023
Including recommendations for
future data stewardship;
diversifying the workforce; and
identifying needs and crosscutting
opportunities

U.S. Department of Energy
and the
National Science Foundation

April 13, 2022

Professor Gail Dodge
Chair, DOE/NSF Nuclear Science Advisory Committee
College of Sciences
Old Dominion University
4600 Elkhorn Avenue
Norfolk, Virginia 23529

Dear Professor Dodge:

This letter is to request that the Nuclear Science Advisory Committee (NSAC) establish an NSAC Sub-Committee to assess challenges, opportunities, and priorities for effective stewardship of nuclear data.

"Nuclear data" is data derived from observed properties of nuclei, their decays and decay products, and the interactions of both nuclei and their decay products with other nuclei, subatomic particles or in bulk matter. Data from theoretical models created for comparison with experimental nuclear data may also be considered for inclusion under this definition.

Increasingly, access to accurate, reliable nuclear data plays an essential role in the success of Federal missions such as non-proliferation, nuclear forensics, homeland security, national defense, space exploration, clean energy generation, and scientific research. Data access is also key to innovative commercial developments such as new medicines, automated industrial controls, energy exploration, energy security, nuclear reactor design, and isotope production. The mission of the United States Nuclear Data Program (USNDP) managed by the Department of Energy (DOE) Office of Science Nuclear Physics (NP) program is to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering. This is accomplished primarily through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. USNDP also addresses gaps in nuclear data, through targeted experimental studies and the use of theoretical models. A keystone of USNDP stewardship of nuclear data is the activity of the National Nuclear Data Center (NNDC) hosted at Brookhaven National Laboratory.

NSAC is requested to develop a strategic plan with prioritized recommendations to guide federal investment in the U.S. Nuclear Data Program (USNDP). This will consist of two separate steps and corresponding reports that will serve as a basis to inform the strategic plan:

How important is this?

Between the last Long Range Plan in 2015 and the July 2022 call for the next one, there were 10 charges to NSAC:

1 on double beta decay;

1 on QC and QIS;

2 on the Committee of Visitors;

6 nuclear data related –

5 on ^{99}Mo plus the general nuclear data charge issued in April 2022

Timing of ND and LRP charges not a coincidence!

Increasingly, access to accurate, reliable nuclear data plays an essential role in the success of Federal missions such as non-proliferation, nuclear forensics, homeland security, national defense, space exploration, clean energy generation, and scientific research. Data access is also key to innovative commercial developments such as new medicines, automated industrial controls, energy exploration, energy security, nuclear reactor design, and isotope production. The mission of the United States Nuclear Data Program (USNDP) managed by the Department of Energy (DOE) Office of Science Nuclear Physics (NP) program is to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering. This is accomplished primarily through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. USNDP also addresses gaps in nuclear data, through targeted experimental studies and the use of theoretical models. A keystone of USNDP stewardship of nuclear data is the activity of the National Nuclear Data Center (NNDC) hosted at Brookhaven National Laboratory.

NSAC is requested to develop a strategic plan with prioritized recommendations to guide federal investment in the U.S. Nuclear Data Program (USNDP). This will consist of two separate steps and corresponding reports that will serve as a basis to inform the strategic plan:

Nuclear data initiative for the Long Range Plan

Nuclear data play an essential role in all facets of nuclear physics. Access to accurate, reliable nuclear data is crucial to the success of important missions such as nonproliferation and defense, nuclear forensics, homeland security, space exploration, and clean energy generation, in addition to the basic scientific research underpinning the enterprise. These data are also key to innovations leading to new medicines, automated industrial controls, energy exploration, energy security, nuclear reactor design, and isotope production. It is thus crucial to maintain effective US stewardship of nuclear data.

- We recommend identifying and prioritizing opportunities to enhance and advance stewardship of nuclear data and maximize the impact of these opportunities.

- We recommend building and sustaining the nuclear data community by recruiting, training, and retaining a diverse, equitable and inclusive workforce.

- We recommend identifying crosscutting opportunities for nuclear data with other programs, both domestically and internationally, in particular with regard to facilities and instrumentation.

NSAC Subcommittee on Nuclear Data

Subcommittee Chair: Lee Bernstein (UC-Berkeley/LBNL)

Subcommittee Members:
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Thanks again to Lee, Dave Brown, Daniel Cebra, Mateusz Ploskon and Michael Smith for inspiring many of the slides shown here!