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U.S. DEPARTMENT OF ENERGY
Office of Science

Nuclear Data for Space Exploration – Part 1

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About me

- Ph.D. in Nuclear Physics from Rutgers University (1994)
- LLNL Post-doc → Staff (1994-2016)
  - Worked at the intersection of basic and applied science
- Joint Faculty Scientist at the UC Berkeley Dept. of Nuclear Engineering and the LBNL Nuclear Science Division.
- I am the Bay Area Nuclear Data Group Leader where I lead a group of 16 researchers and students who work to address the nuclear data needs of the applied and basic science community.
- Background in low energy nuclear structure, nuclear reactions and plasma physics
- I've been part of a nuclear data outreach effort to the nuclear energy, isotope production, counterproliferation and ***space*** communities through a series workshops and meetings including NDNCA (2015)[1], NDREW (2018)[2] and WANDA (2019, 2020, 2021) [3]
- As a new NSAC member I was asked to *"provide expert advice in the field of nuclear science, as it relates to nuclear data needs of the applied and basic science and engineering with specialization in measuring low-energy nuclear properties and cross sections"*

[1] https://bang.berkeley.edu/events/ndnca

[2] https://info.ornl.gov/sites/publications/Files/Pub111600.pdf
[3] https://nucleardata.berkeley.edu/wanda/index.html

We decided that a "tag team" approach is the best way to show the way that RHIC can address nuclear data needs for space exploration

1. Introduction:
   - The space environment and the role of shielding
   - Dose and the importance of stopping powers
   - The nuclear data evaluation process

UC/LBNL Nuclear Data Group Leader

Lee Bernstein (UC/LBNL)

2. Particle Transport:
   - The transport code universe
   - Reaction modeling from 10^{-3} – 10^{10} eV
   - The role of the US Nuclear Data Program

National Nuclear Data Center Group Leader

Dave Brown (BNL)

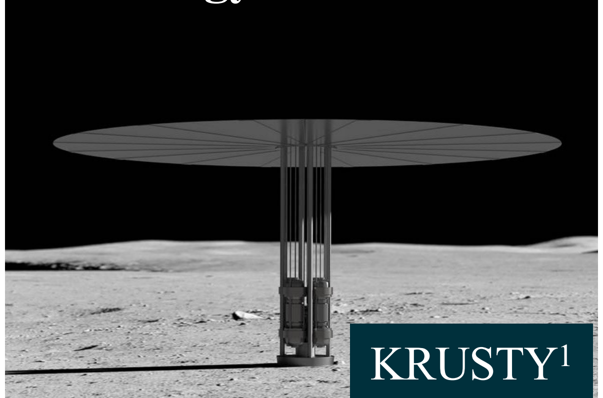
3. The role of RHIC
   - The STAR fixed target station
   - The type of data that can be provided
   - How RHIC can help provide the high-energy "Source term" for space shielding applications

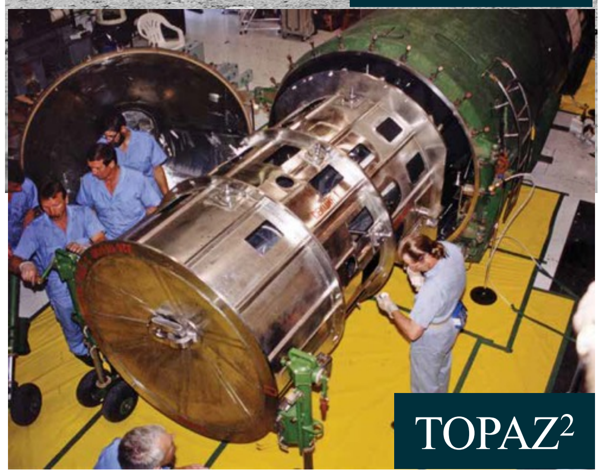
STAR fixed target program leader

Dan Cebra (UC Davis)

Nuclear Data is central to Space Exploration

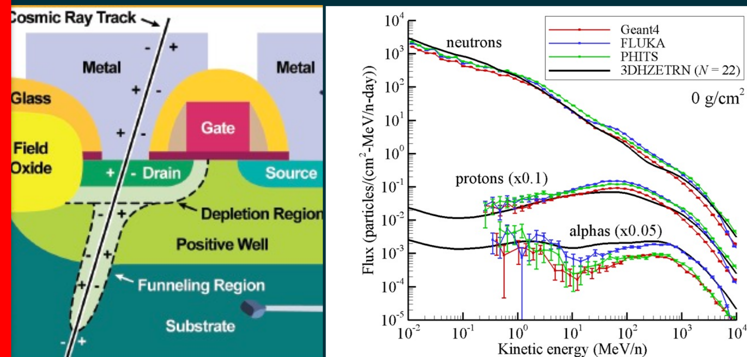
Energy Production





[1]https://www.nasa.gov/directorates/spacetech/kilopower
[2]*Thermionics Quo Vadis? an assessment of DTRAs advanced thermionics research and development program.* Washington, D.C. National Academy Press. (2001).

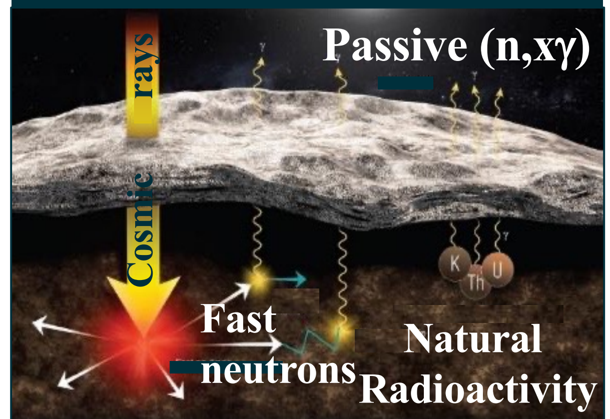
Dose/Shielding Calculations for Electronics[4] and Humans[5]



Nuclear Data

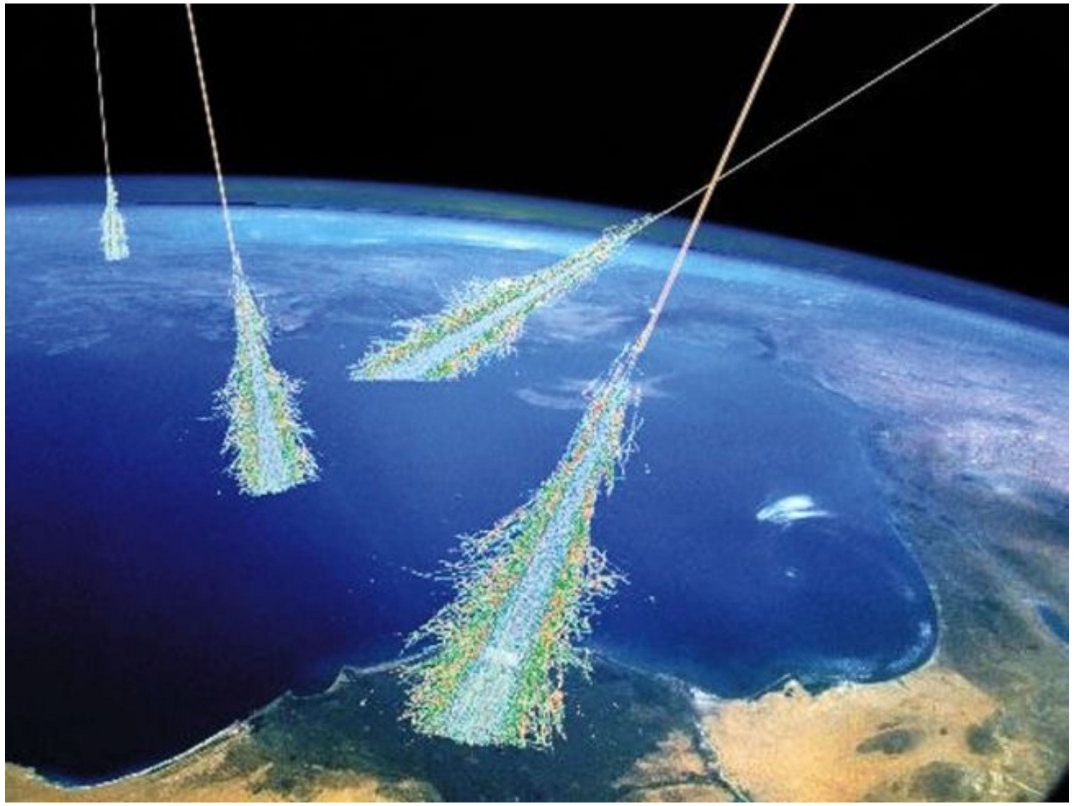
Nuclear Propulsion

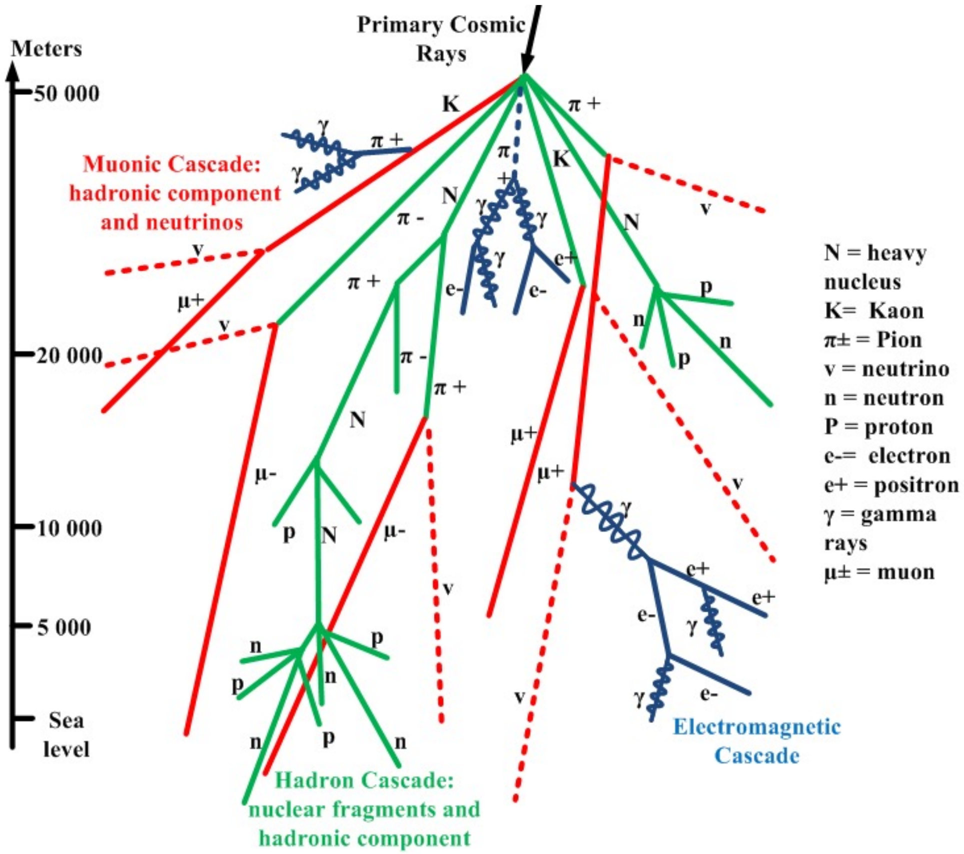
Elemental ID using neutron-induced γ-rays[3,4]



[3]C. Romano *et al.*, WANDA 2020 Final Report. ORNL/TM-2020/1617 (2020).
[4]P. Peplowski (JHUAPL) numerous

We are shielded from the Galactic Cosmic Ray Background by our atmosphere and the earth's magnetic field



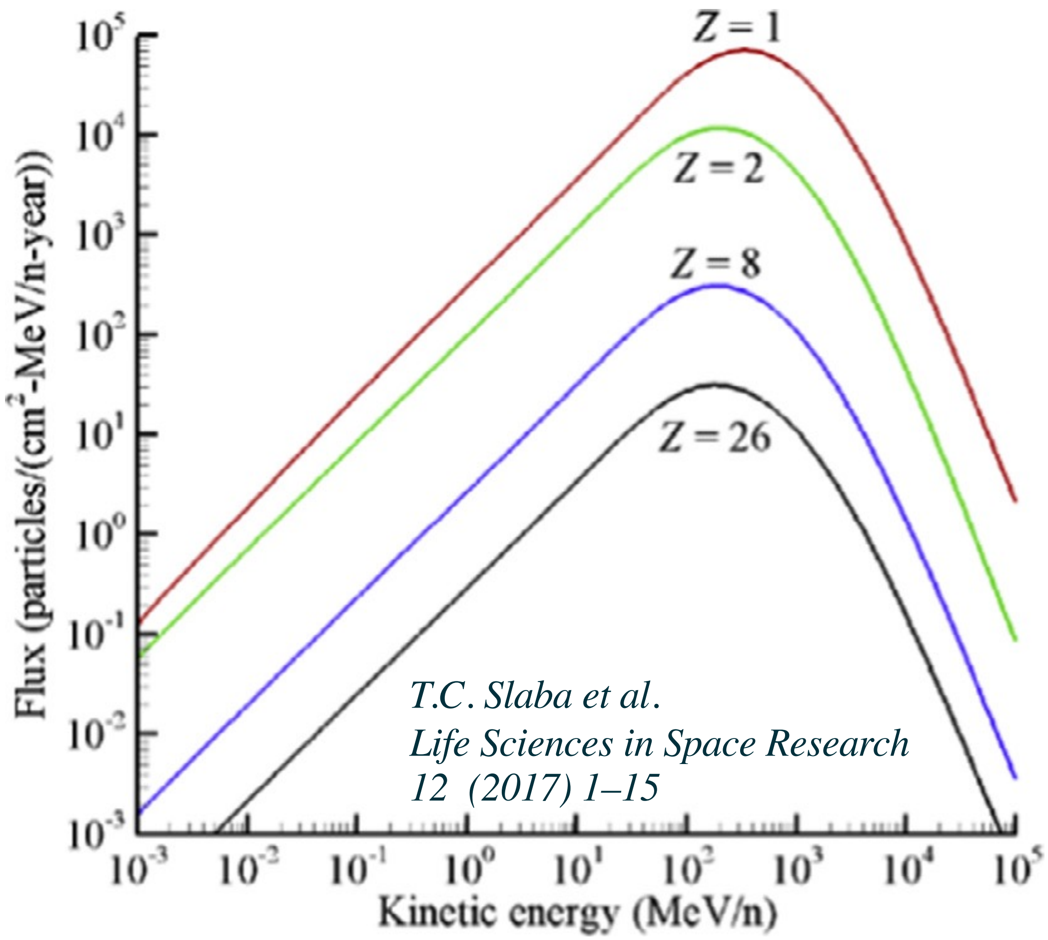


What is this Galactic Cosmic Ray Background comprised of?

Daniel Gomez Toro. Temporal Filtering with Soft Error Detection and Correction Technique for Radiation Hardening Based on a C-element and BICS. Micro and nanotechnologies/Microelectronics. Télécom Bretagne; Université de Bretagne Occidentale, 2014. English. tel-01191520

The GCR background spans a huge mass and energy range covering virtually all of Nuclear Physics

- The GCR includes nuclei as heavy as ^{56}Fe and E/A up to 50 GeV
  - For reference, $E_{binding}(^{56}Fe) \approx 0.5$ GeV
  - The range of 1 *GeV* proton in Al is > 1 m.
- It's even worse near the gas giants where their magnetic field meets the solar wind.
- These high-energy particles create cascades of *hundreds* of secondary, tertiary etc. particles
  - The shielding itself can contribute to the variety of secondary particles produced.
  - Charged secondary particles deposit a portion of their energy more locally than neutrons

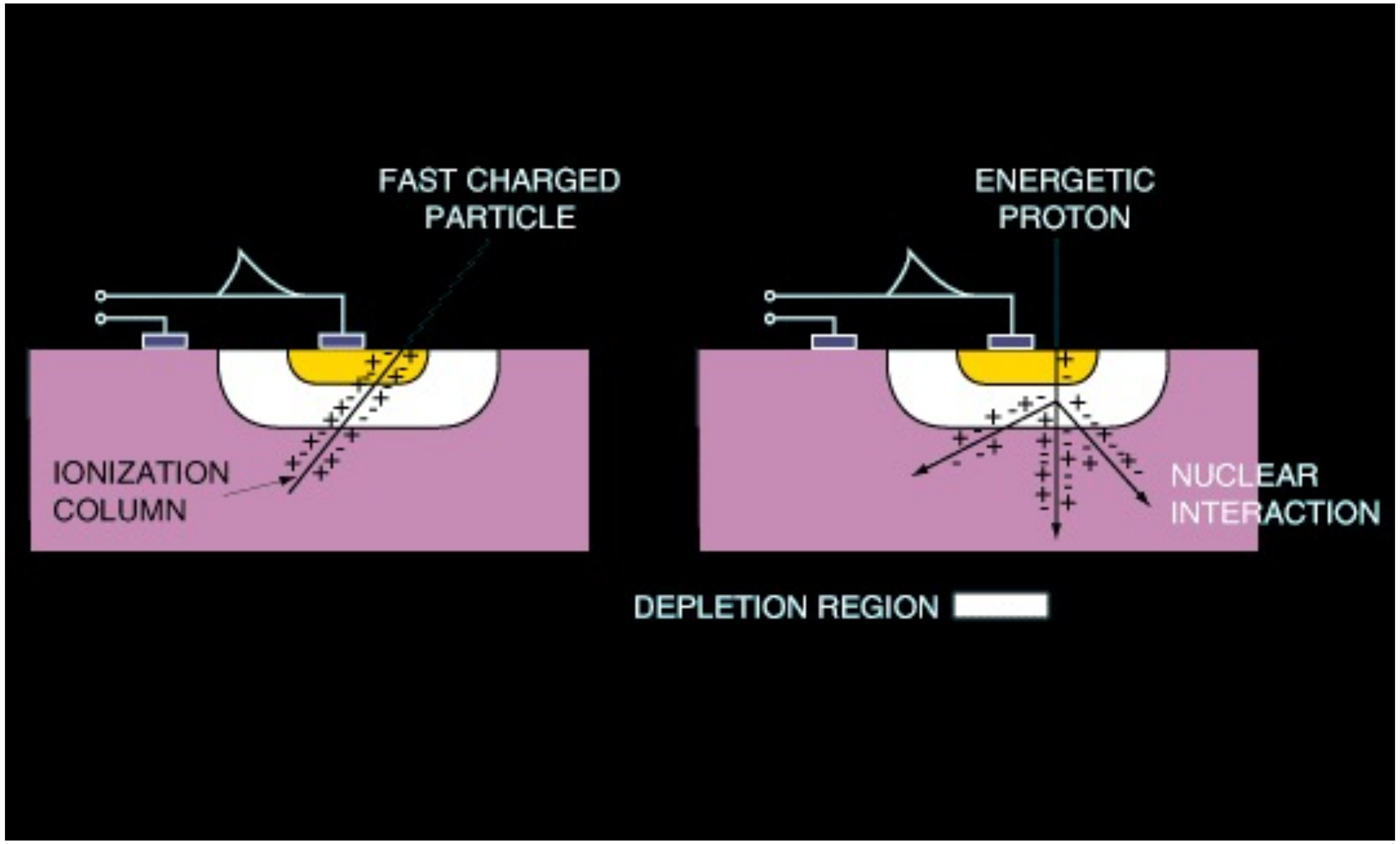


The solar system beyond the atmosphere and the earth's magnetic field is a tough neighborhood!

Space exploration requires appropriate shielding over a wide range of energy

What is the effect of the GCR on electronics?

- GCRs can cause *single event upsets (SEU)* in transistors that can cause temporary or permanent failures.
- The likelihood of an SEU increases with dose density.
- GCR heavy ions cause a local, dense ionization column
- Secondary protons and neutrons can induce a nuclear reaction that creates a recoiling residual nucleus
- The imparted dose depends on the *stopping power* of the recoiling nuclei.



M. Lauriente, A. L. Vampola, "Spacecraft anomalies due to radiation environment in space," NASDA/JAERI 2nd International Workshop on Radiation Effects of Semiconductor Devices for Space Applications, Tokyo, Japan, March 1996.

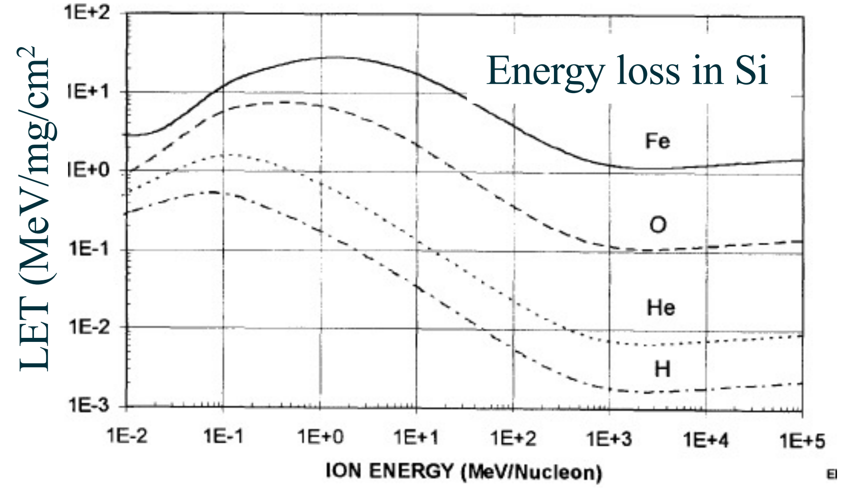
Energy deposition from charged particles in a material is quantified by the *Linear Energy Transfer* (LET)

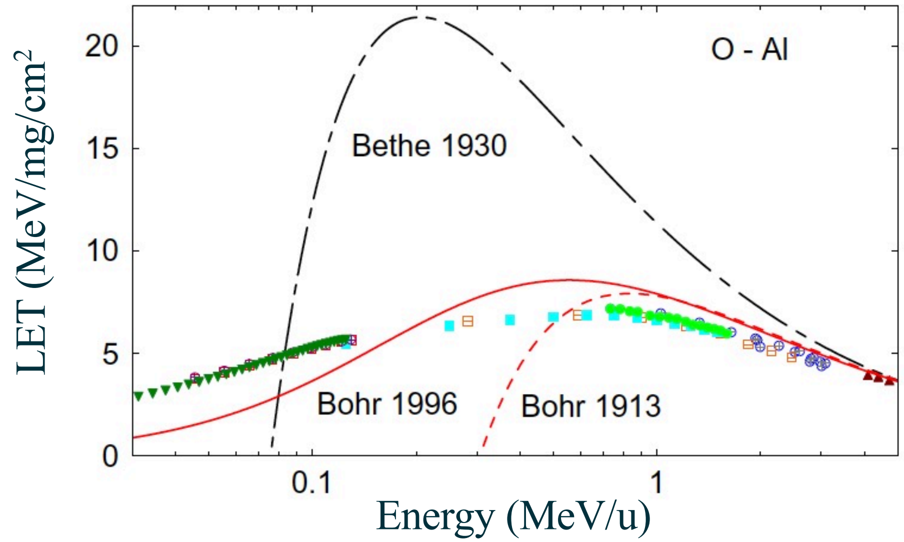
Linear Energy Transfer (LET) is the ratio of energy transferred by a charged particle (dE_{local}) to target atoms along its path (dx). Units are energy/thickness, e.g., MeV/cm or MeV/mg/cm^2

As the energy of an ion → 0 the stopping power increases, leading to a *Bragg Peak* where the highest dose is deposited

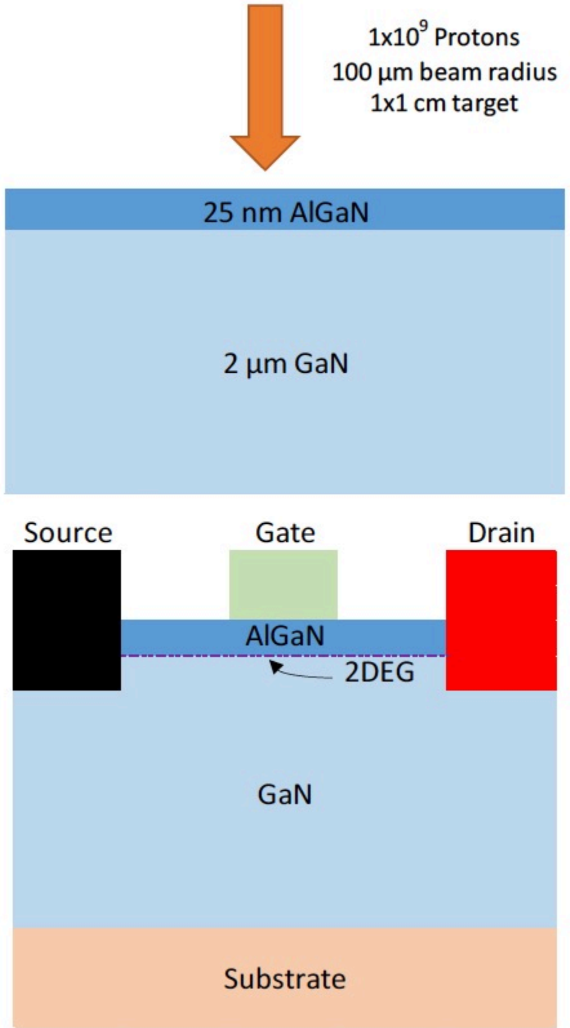
Higher-Z ions have shorter ranges and higher dose in their Bragg Peaks

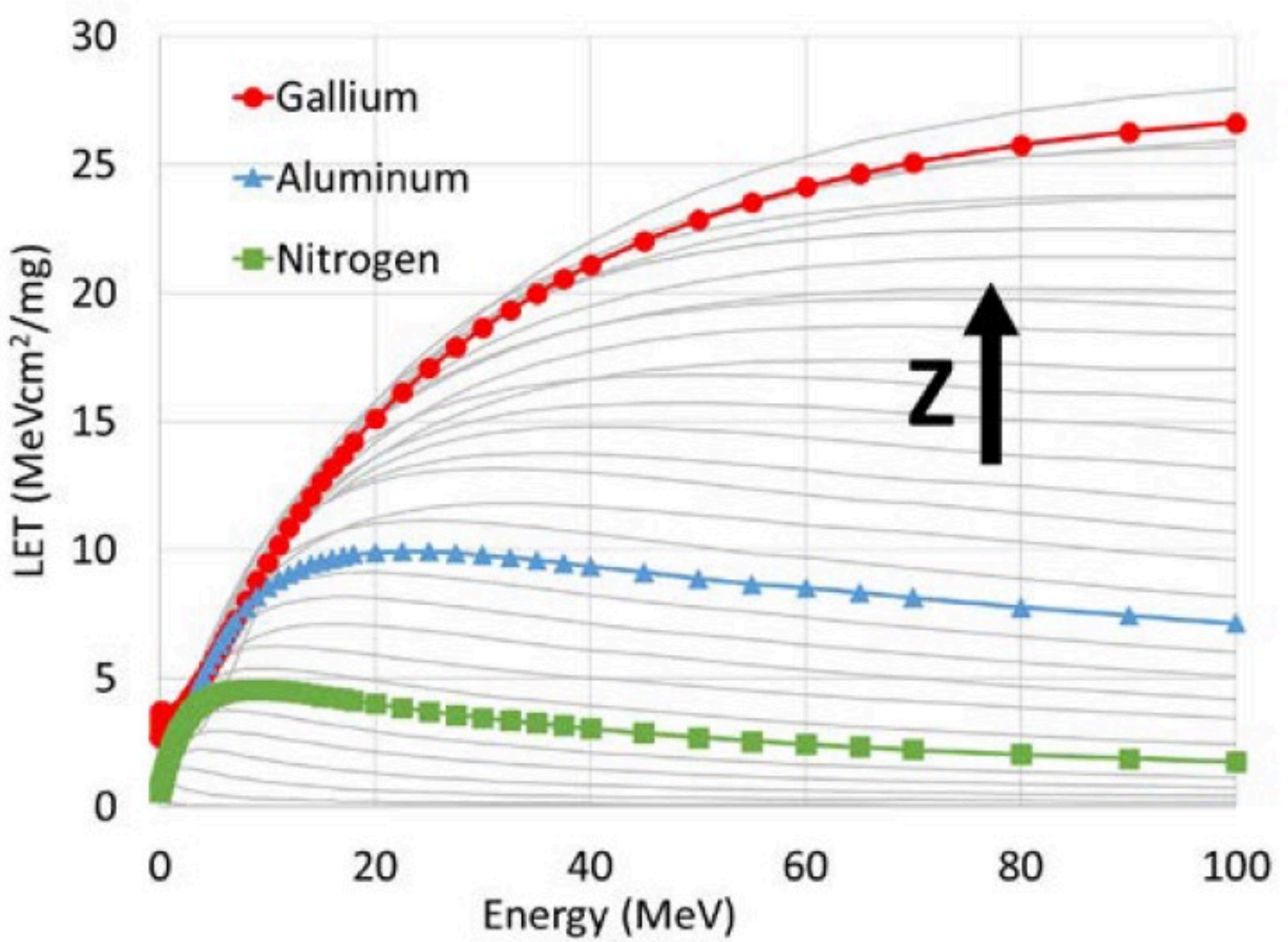
*"…the credibility of SRIM (the primary stopping power code used) predictions may decrease dramatically in regions of the Z, Z_{target}, E parameter space that is unsupported by experimental data."**





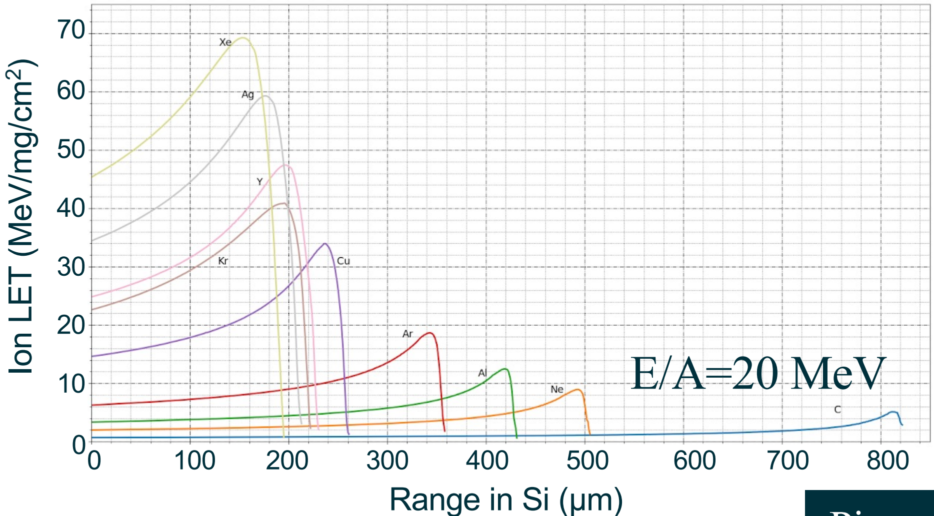
Recently *Osheroff et al.*, showed that the LET in AlGaN electronics is dominated by recoiling high mass nuclei





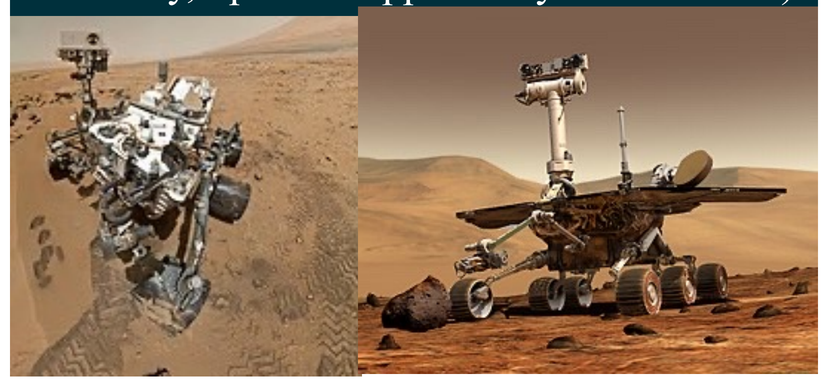
J.M. Osheroff et al. IEEE Transactions on Nuclear Science Volume: 68, Issue: 5, May 2021

NASA uses “Cocktail” beams of multiple heavy-ions to uniformly dose electronics to test their radiation hardness for use in spacecraft



Mercury Messenger

Curiosity, Spirit & Opportunity Rovers Mars)

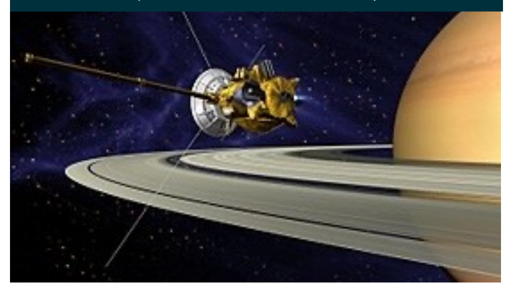


The LBNL 88-Inch cyclotron*

Pioneer (Venus)

Galileo (Jupiter)

Cassini/Huygens (Saturn/Titan)



New Horizons (Pluto)

These are integral tests and don’t add to our understanding of the GCR or the secondary particles it creates

Human radiation damage depends on *Dose Equivalency*

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

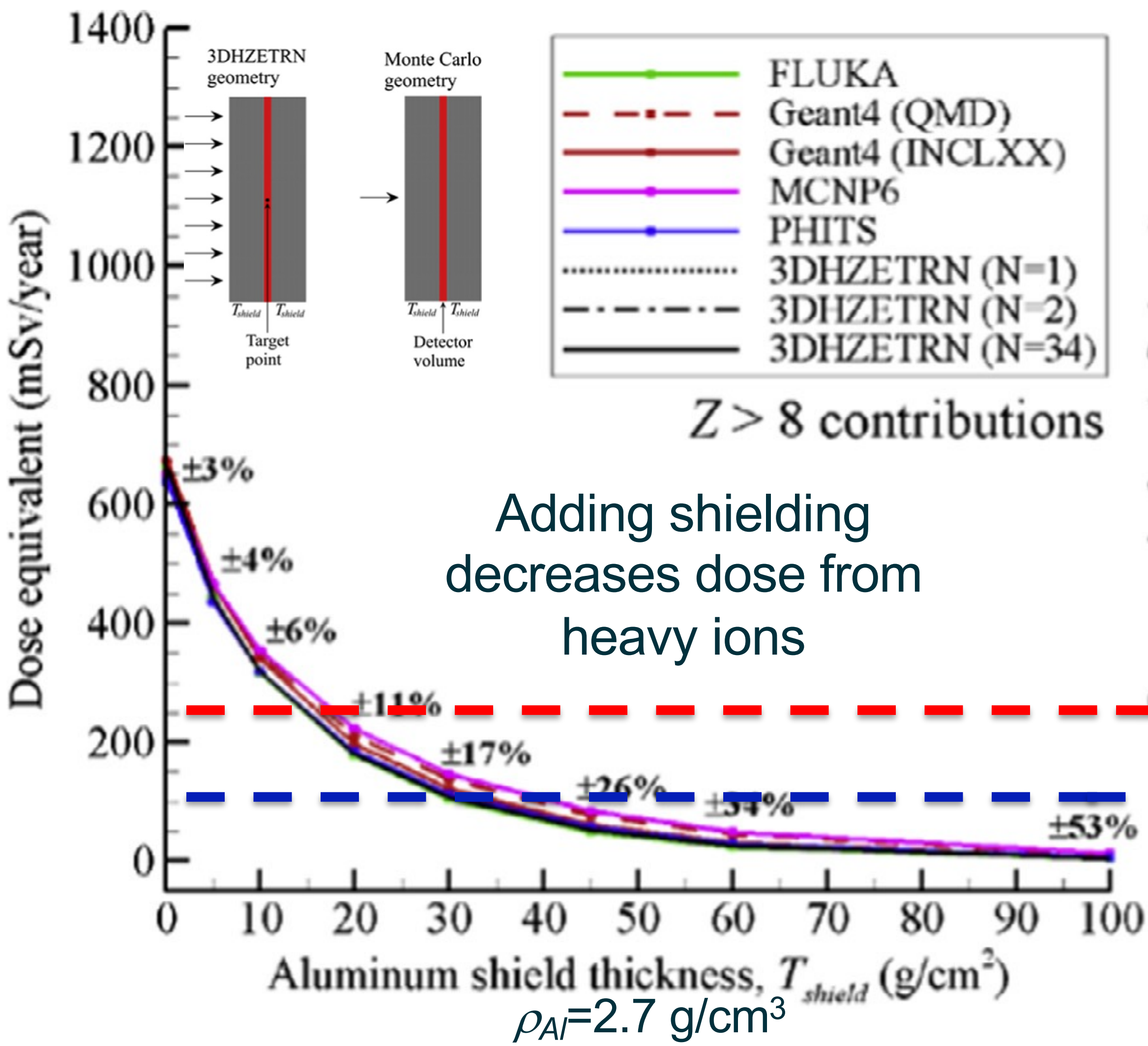
$$Dose\ Equivalent\ = \mathrm{D}{\times}Q\ (REM)$$

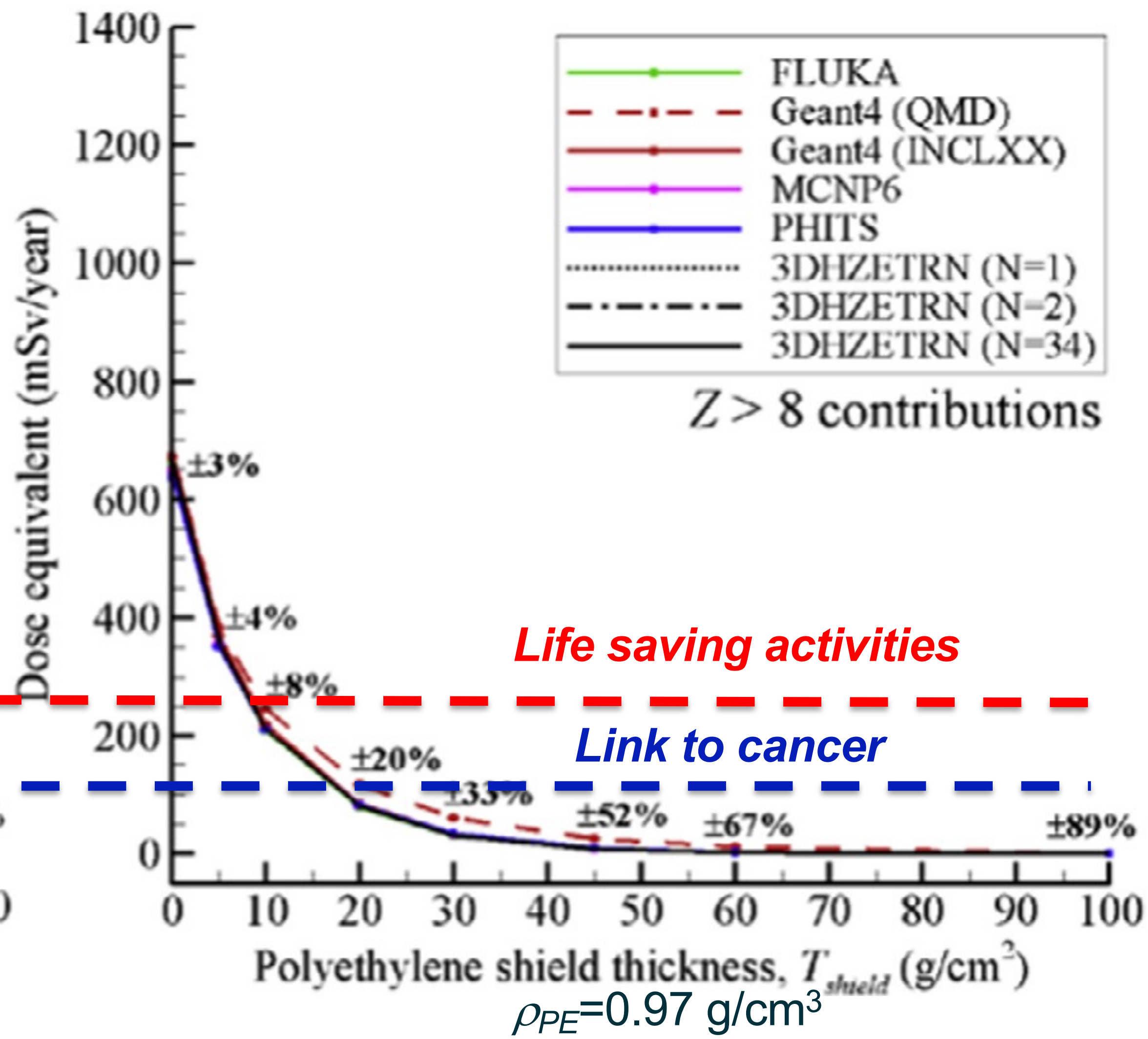
$$Q_{\gamma-rays} = 1, Q_{\alpha} = 20$$

$$1\ Sievert = 100\ REM$$

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

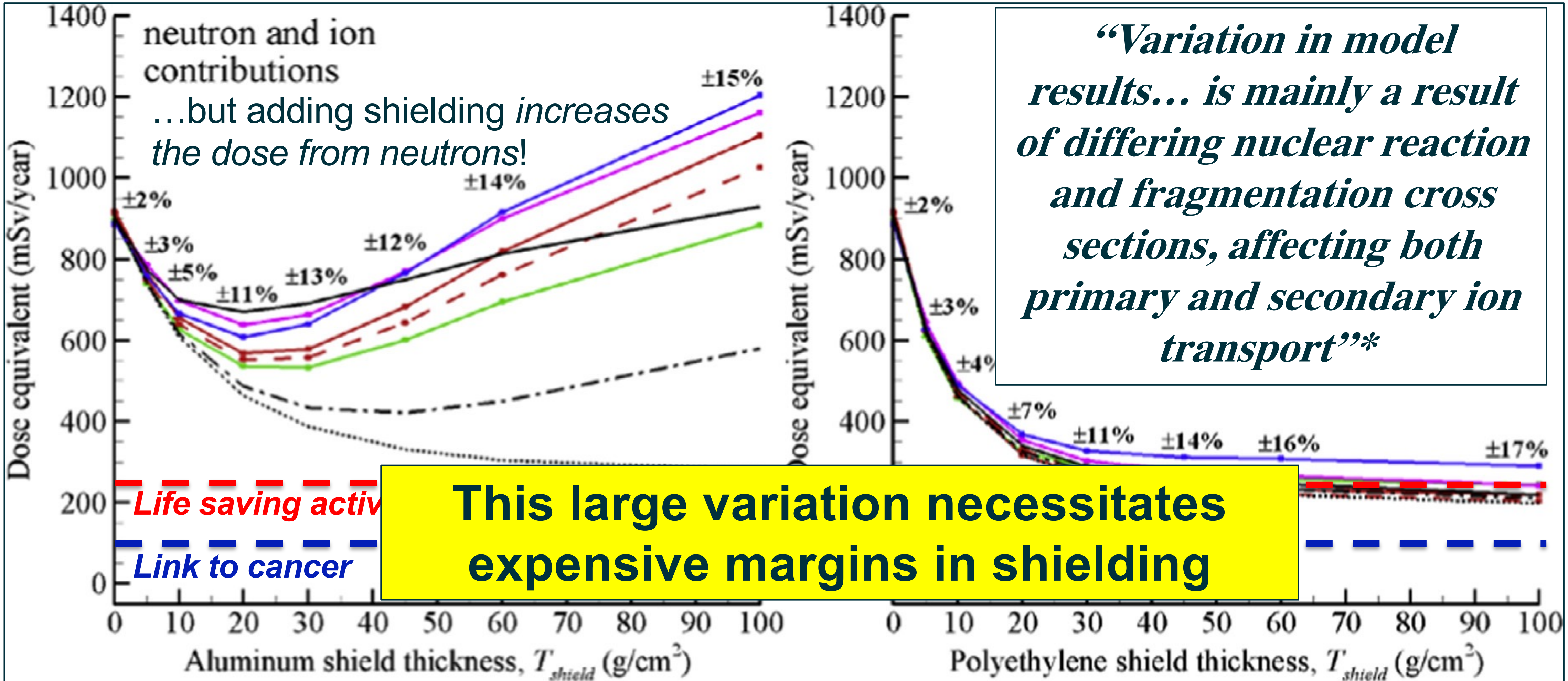
The effects of shielding* for projectile-like fragments (Z>8)





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

The effects of shielding* from 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"*

This large variation necessitates expensive margins in shielding

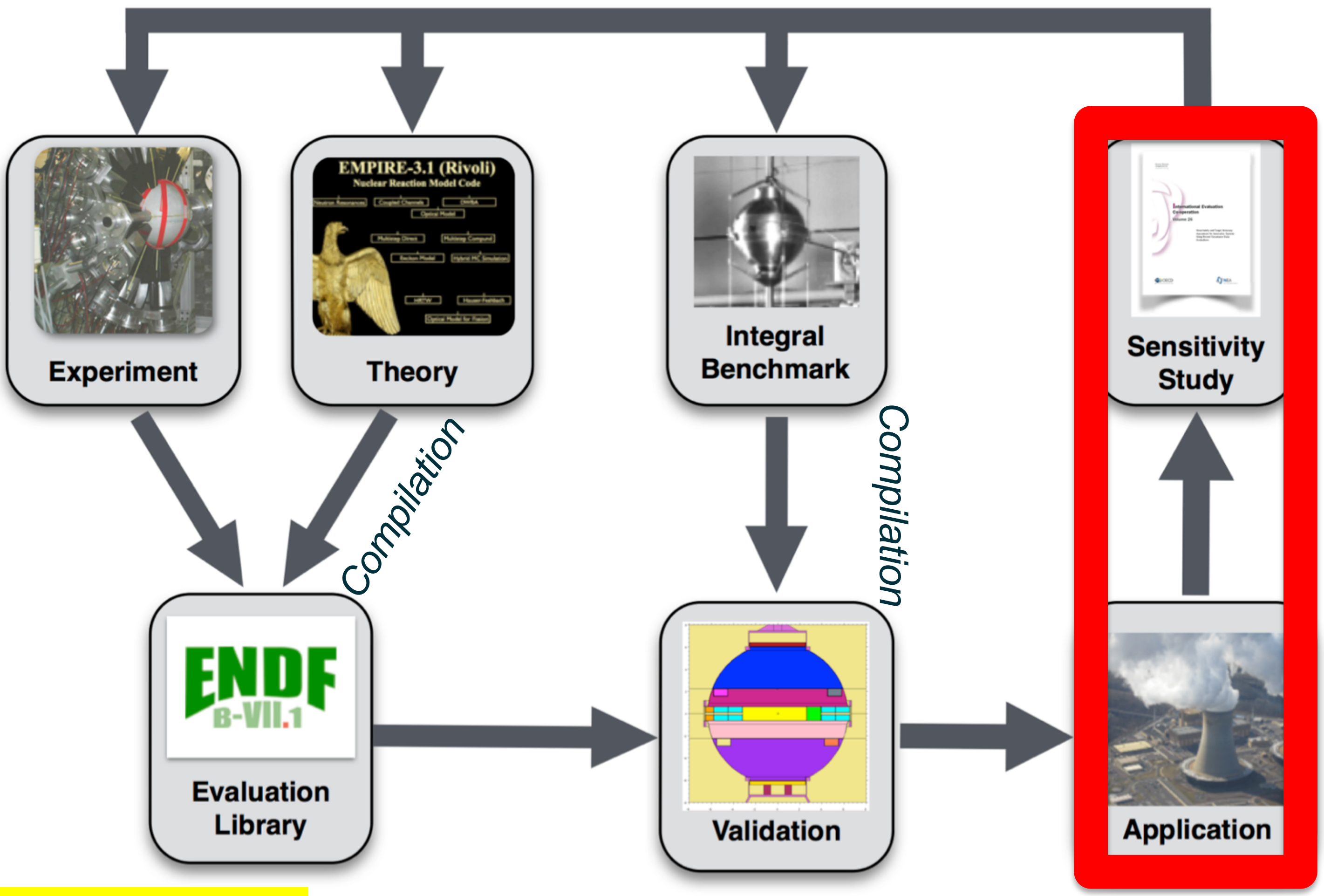
ρ_{Al}=2.7 g/cm^3

ρ_{PE}=0.97 g/cm^3

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

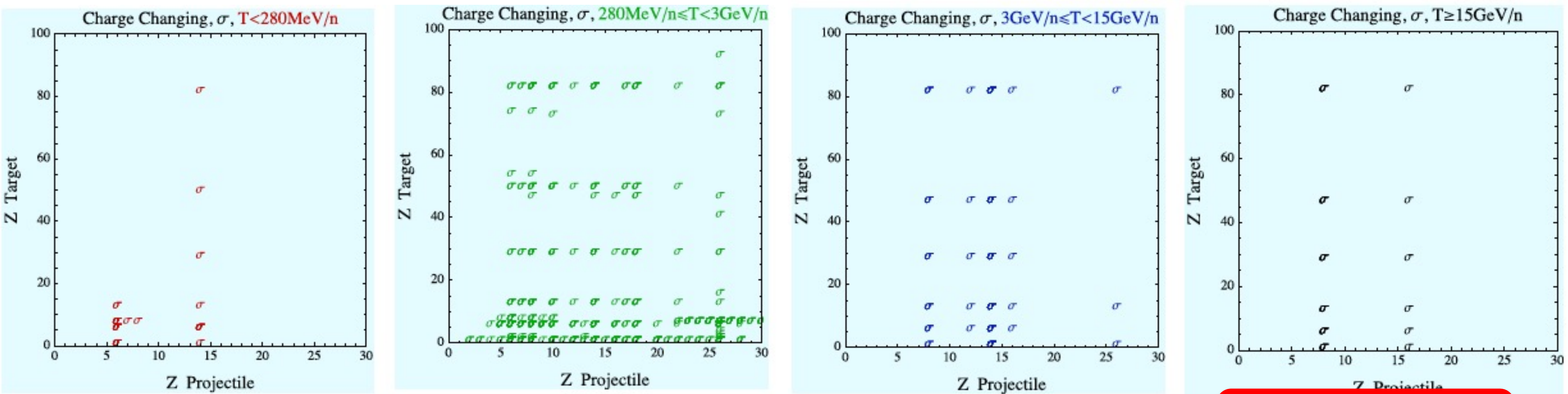
The nuclear energy community have addressed nuclear data needs via experiment-guided modeling called ***evaluation***

- A _sensitivity study_ is performed for a specific application performs to determine what new _experiments_ are needed.
- Published experimental data (including uncertainties) are compiled into databases (EXFOR).
- Physics-based theoretical models are adjusted to best reproduce differential measurements (cross section vs. energy, fission yields etc.) and produce an _evaluated data library_
- These values are used to model integral benchmarks (critical assemblies etc.) for _validation_.



NASA has already started this process!

Norbury *et al.** have shown that large gaps exist in experimental data needed for shielding optimization



*This work contains **64 plots** showing the total, charge-changing, elemental and isotopic cross sections needed*

Cross-section	Fragment	Below π threshold projectile	Low energy projectile	Medium energy projectile	High energy projectile
σ	He	All	He,O,Si,Fe(T)	All	All
	^{3}He	He(T),C,O(H),Si,Fe	He(H̸),O(T),Si,Fe	He(H),C(H̸),O,Si,Fe	All
	^{4}He	He(T),C,O(H),Si(H̸),Fe	He,Si(H̸),Fe	He,C(H̸),O,Si,Fe	All
	^{6}He	All	He,O(T),Si,Fe	He,C(H̸),O,Si(H),Fe	All
$dE/d\Omega$	He	All	All	All	All
	^{3}He	He(H),C,O(H),Si,Fe	O,Si,Fe	All	All
	^{4}He	He(H),C,O(H),Si,Fe	O,Si,Fe	All	All
	^{6}He	All	He,O,Si,Fe	All	All

Cross-section	Fragment	Below π threshold projectile	Low energy projectile	Medium energy projectile	High energy projectile
σ	H	All	He,O,Si,Fe(T)	All	All
	^{1,2,3}H	He(T),C,O(H),Si,Fe	He(H̸),O(T),Si,Fe	He(H),C(H̸),O,Si,Fe	All
$dE/d\Omega$	H	All	All	All	All
	^{1,2,3}H	He(H),C,O(H),Si,Fe	O,Si,Fe	All	All

"All" projectiles signify He, C, O, Si, Fe

This is where STAR @ RHIC can really help!

And now onto Dave…

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*J.W. Norbury *et al.*
Radiation Measurements 47 (2012) 315e363