Space Radiation Transport Codes: Comparisons & Model Sensitivities to Nuclear Data

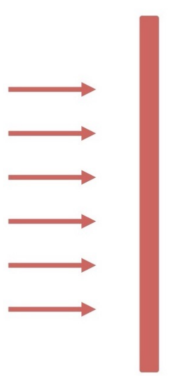
Zi-Wei Lin
Department of Physics
East Carolina University
Greenville, NC

Compare Space Radiation Transport Codes

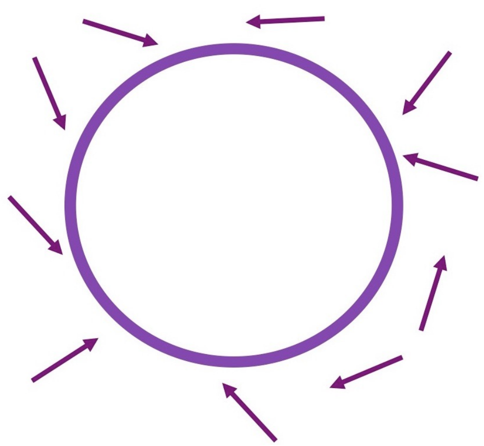
We have compared dose, dose equiv. & spectra of

- **4** transport codes:
  1-d deterministic: HZETRN (1995), UPROP,
  3-d Monte Carlo: FLUKA, Geant4.
- **3** space radiation environments:
  Oct. 1989 SPE, Jan. 20 2005 SPE,
  1977 solar minimum GCR.
- 2 shielding materials:
  aluminum (Al), polyethylene (CH_2).
- 2 geometries:
  slab, spherical shell (10g/cm^2, r=1.5m)

a)



b)

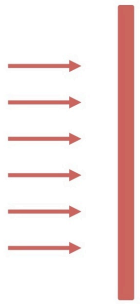


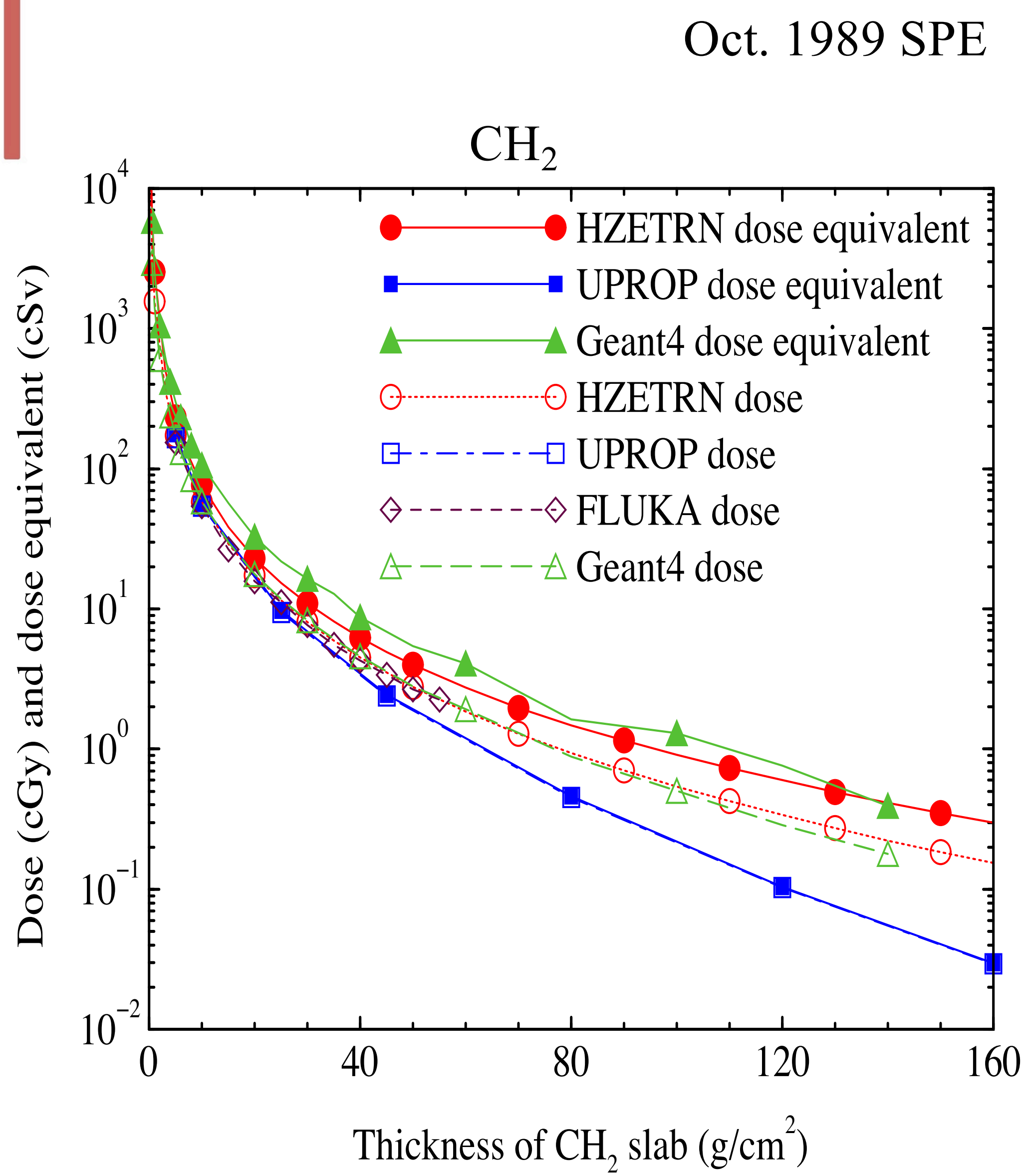
ZWL, Adams Jr., Barghouty, Randeniya, Tripathi, Watts & Yepes, Adv Space Res 49 (2012)

Other comparison studies include

- HZETRN vs HETC & FLUKA, in Heinbockel et al., Adv Space Res 47 (2011)
- OLTARIS vs MCNPX & PHITS, in Aghara et al., Life Sci Space Res 4 (2015)
- HZETRN vs Geant4, in Gronoff, Norman & Mertens, Adv Space Res 55 (2015)
- HZETRN vs SHIELD, FLUKA & Geant4, in Norbury et al., Life Sci Space Res 14 (2017)
- Geant4 vs 3DHZETRN, Slaba et al., Life Sci Space Res 27 (2020),
- …

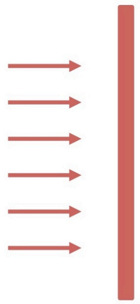
Comparing transport codes: slab geometry



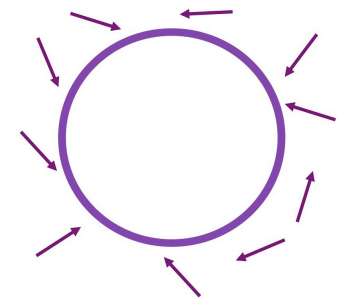


- Dose values from HZETRN, FLUKA and Geant4 are ~ consistent,
- Dose from UPROP is lower behind thick shielding.

- Dose equivalent from Geant4 are often higher than HZETRN.
- Dose equivalent from UPROP behind shielding are much lower (*UPROP has no neutrons*).

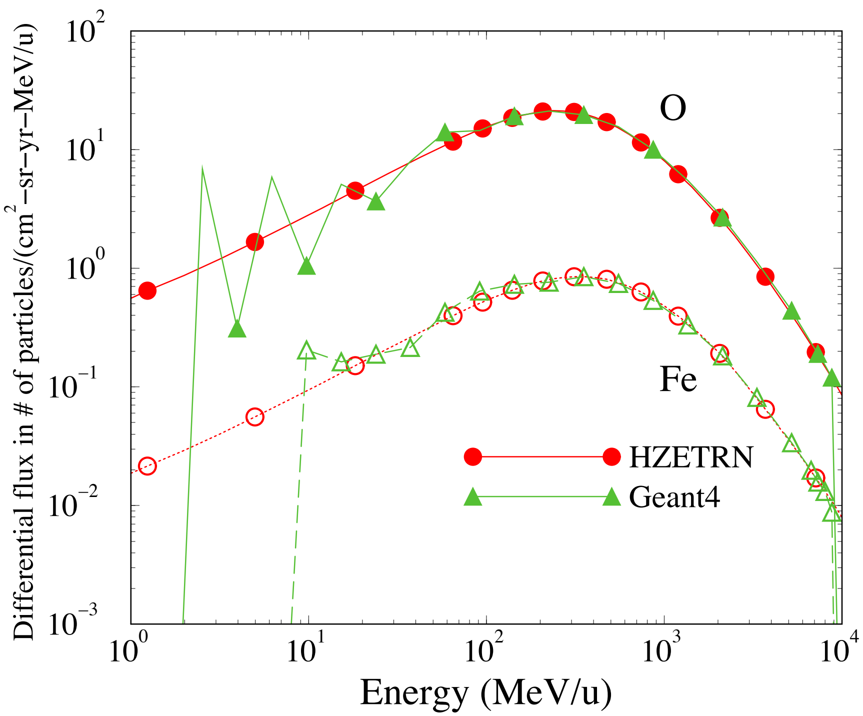


Comparing transport codes: ion spectra

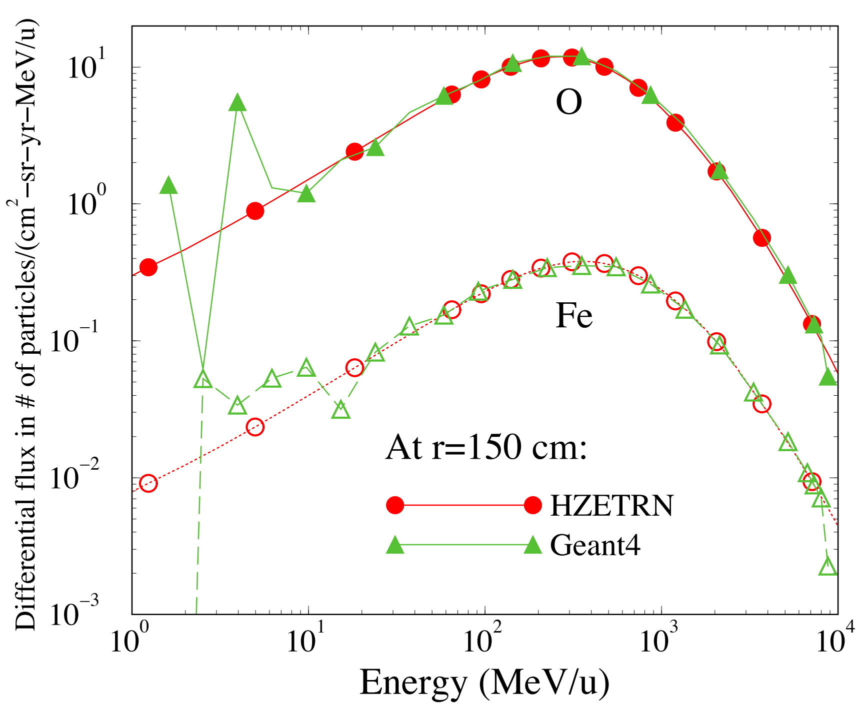


1977 solar minimum GCR

Behind 10g/cm^2 Al slab:

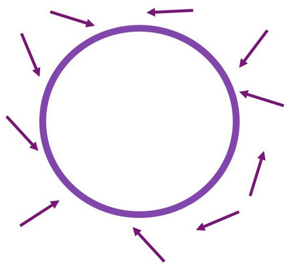


At inner wall of a spherical 10g/cm^2 Al shell (*average thickness 27.3g/cm^2*):

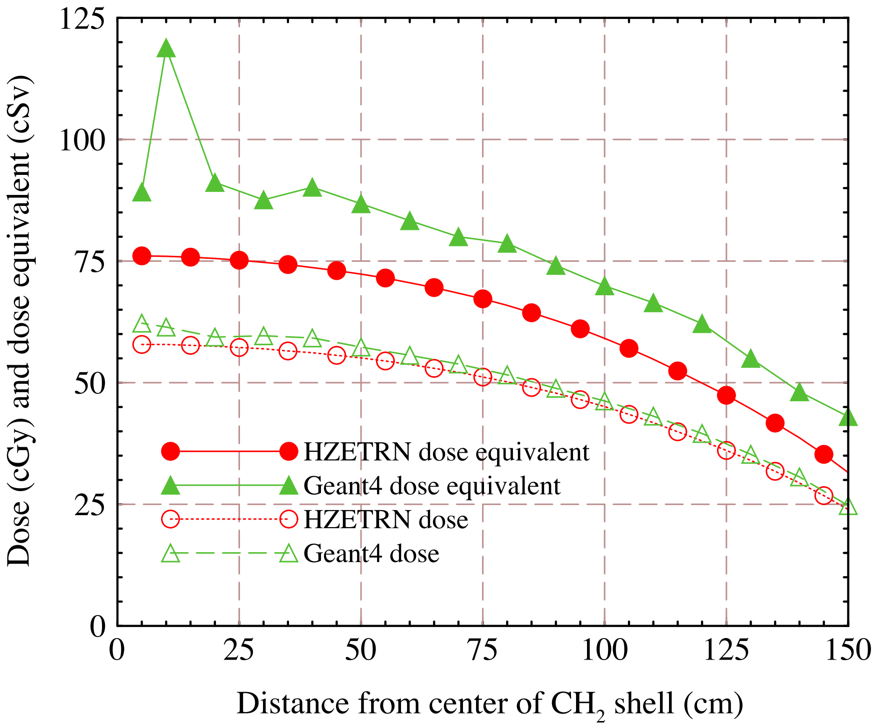


HZETRN and Geant4 are consistent.

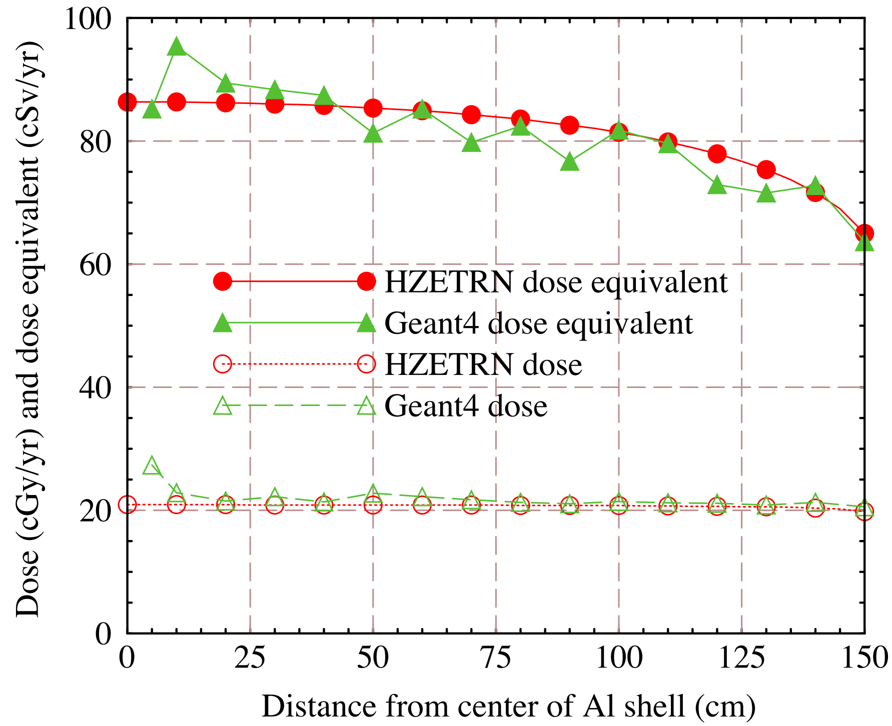
Comparing transport codes: shell geometry



CH_2
Oct. 1989 SPE



Aluminum
1977 solar minimum GCR



- Dose values from HZETRN and Geant4 agree.
- Dose equivalent from HZETRN & Geant4 are close for aluminum, but Geant4 are higher than HZETRN for CH_2.

A key goal of comparison studies is to identify the physics models/components, which cause the differences in the transport model results, for future improvements.

Model Sensitivities to Nuclear Data

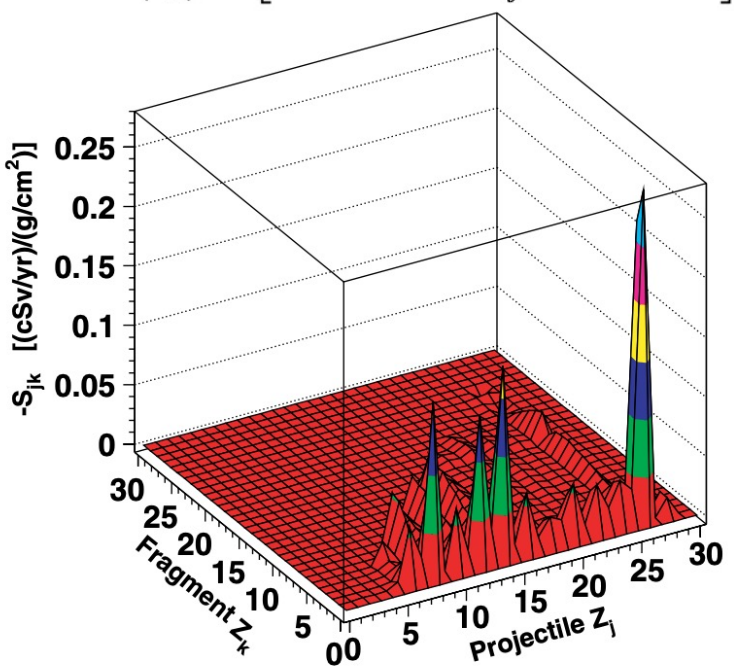
1d propagation equation (Λ_{kj}=1/nσ_{kj}):

$$\frac{\partial J_k(E,x)}{\partial x} = -\frac{J_k(E,x)}{\Lambda_k(E)} + \sum_j \frac{J_j(E,x)}{\Lambda_{kj}(E)} + \frac{\partial[\omega_k(E) J_k(E,x)]}{\partial E}$$

→ Sensitivity matrix S_{jk} (for dose equiv. H):

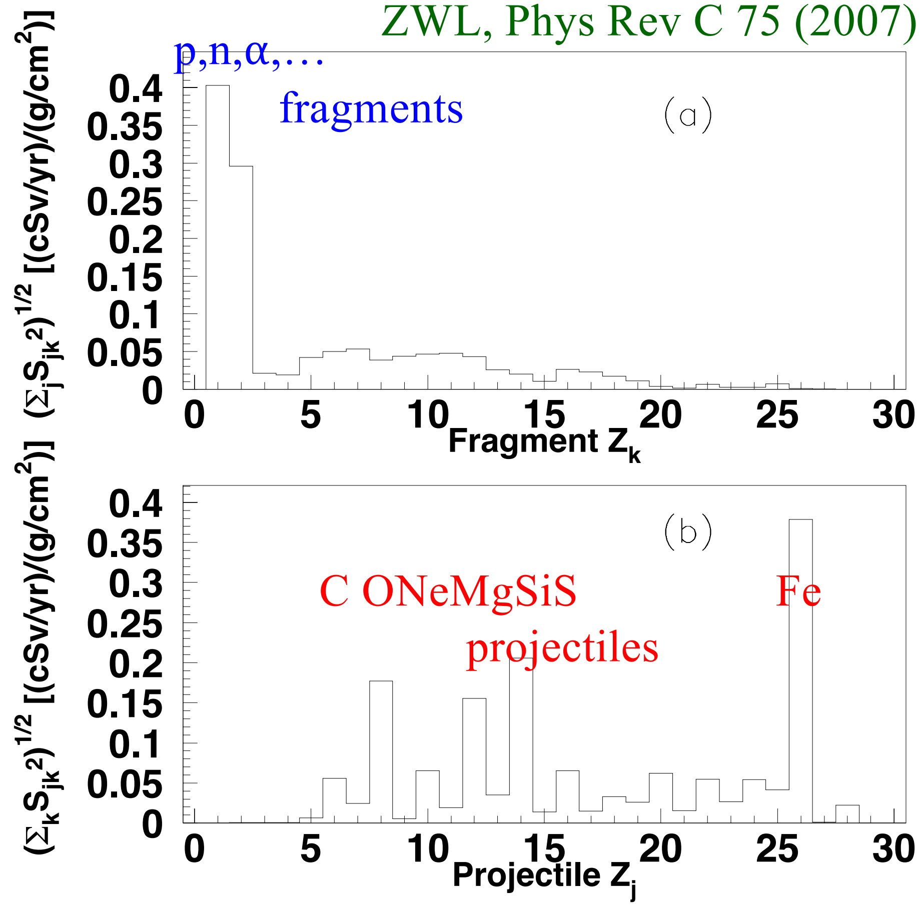
$$\delta H(x) \equiv \rho x \sum_{j,k} S_{jk} \frac{\delta\sigma_{kj}}{\sigma_{kj}},$$

$$S_{jk} = \frac{n}{\rho_T \rho} \int J_j \left[-Z_j^2 Q(Z_j^2 L_1) \frac{A_k}{A_j} + Z_k^2 Q(Z_k^2 L_1) \right] L_1 \sigma_{kj} dE.$$



→1-d projections

ZWL, Phys Rev C 75 (2007)



Partial cross section to light fragments (e.g. nucleons & α) are by far the most important.

Several projectiles are important (e.g. O, Mg, Si, Fe).

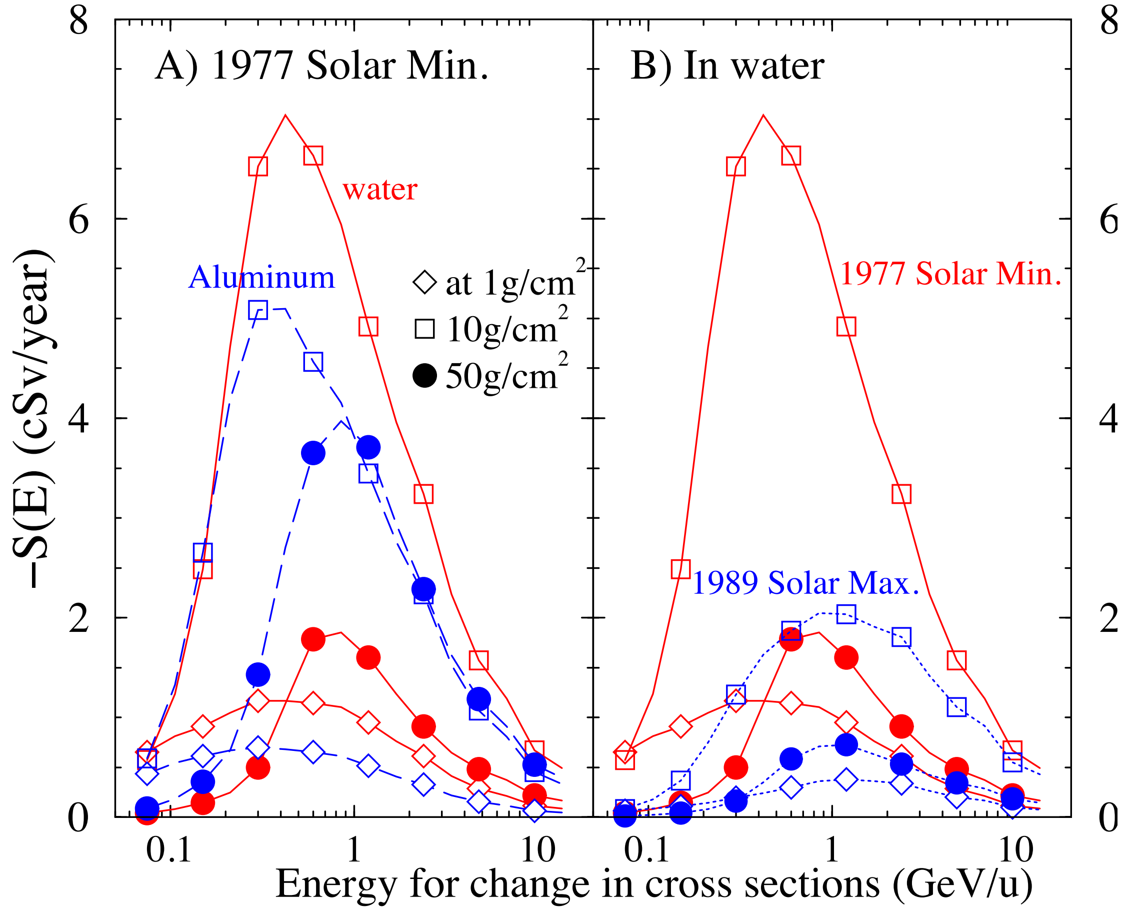
Model Sensitivities to Nuclear Data

Sensitivity function in energy *S(E)*
(for dose equiv. *H*):

$$H = \sum_k \int J_k(E) L_k(E) Q[L_k(E)]\, dE,$$

$$\delta H = \int S(E) \frac{\delta\sigma(E)}{\sigma(E)}\, d(\ln E).$$

ZWL & Adams Jr., Radiat Res 167 (2007)



Cross sections in a wide energy range ~(0.1, 10) GeV/u are all important,
with the radiation risk being most sensitive to cross sections at (lab-frame) energy of
~ (0.3, 0.85) GeV/u in solar minimum GCR environments,
~ (0.85, 1.2) GeV/u in solar maximum GCR environments.

Further Studies Helpful for Space Radiation Transport

Nuclear cross section data:

Results from sensitivity studies need to be combined with available cross section data to identify:

what important cross sections are missing or need to be better measured.

Norbury et al., NASA/TP (2011),
Norbury & Miller, Health Phys 103 (2012),
Slaba & Blattnig, Space Weather 12 (2014),
Norbury et al. Front Phys 30 (2020), …

Space radiation transport codes:

- Transport codes in general need to use theoretical nuclear physics models for fragmentation as well as secondary particle productions (*pions, kaons, anti-nucleons, …*) that are tuned to double-differential experimental data.

- → Synergy with relativistic heavy ion collisions: especially because of the recent/future focus of relativistic heavy ion physics on high net-baryon density physics *(at energies that overlap with space radiation physics)* & renewed interests in light nuclei productions (^{2}H, ^{3}H, ^{3}He, ^{4}He, …).

- It could also be useful to develop "fast Monte Carlo" codes *(faster than normal Monte Carlo & more accurate than deterministic),* this can benefit from such works in radiation therapy research.

Muraro et al. Front Phys 25 (2020), …