Space Radiation Transport Code Development: 3DHZETRN

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2015 HRP Investigators' Workshop
Jan 13-15, 2015
Galveston, TX

Outline

- Overview
- 3DHZETRN formalism
- Comparison to Monte Carlo (MC) codes
- Summary

Overview

- NASA's space radiation transport code, HZETRN, has been used extensively in a variety of applications
  - Research
  - Vehicle design and optimization
  - Operations and risk assessment

- HZETRN is a deterministic model allowing a converging sequence of physical approximations to be implemented
  - Direct solution of the Boltzmann equation using method of characteristics
  - Straight-ahead approximation (extensive verification and validation)
  - Bi-directional transport extension (extensive verification, limited validation)
  - <u>3D transport extension (limited verification) → present focus</u>

- Transport extensions beyond straight-ahead approximation based on forward/isotropic interaction model
  - Neutron production terms can be represented as a sum of forward and isotropic components
  - 3D extension allows for integration of full angular dependence (future work)

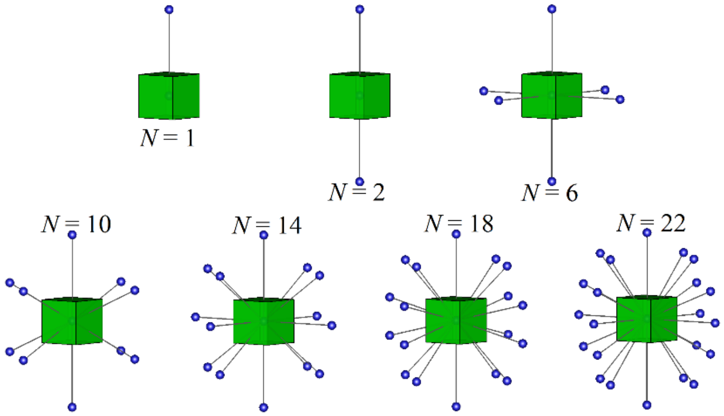
3DHZETRN Formalism

- Neutron production cross section is separated into forward and isotropic components

- Forward component of flux is solved within the straight-ahead approximation
  - at any point within the geometry

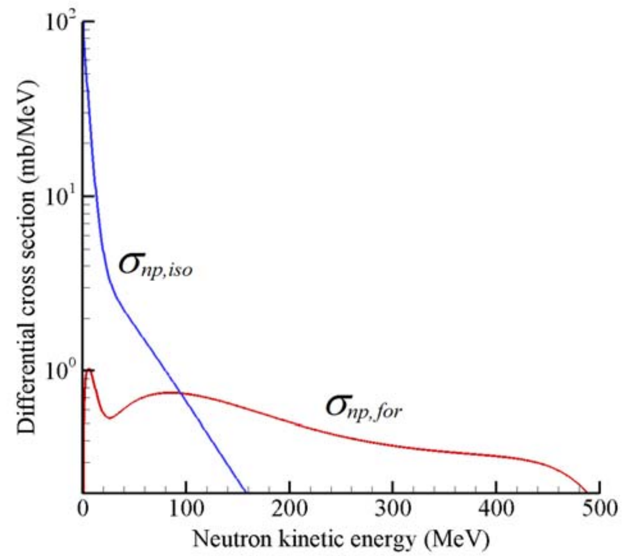
- Forward flux generates isotropic neutron source term
  - at any point within the geometry

- Isotropic neutron field described with *N* stream directions
  - Bi-directional neutron transport (*N*=2) implemented along anti-parallel rays
  - Final step evaluates/transports light ion target fragments produced from isotropic neutron field

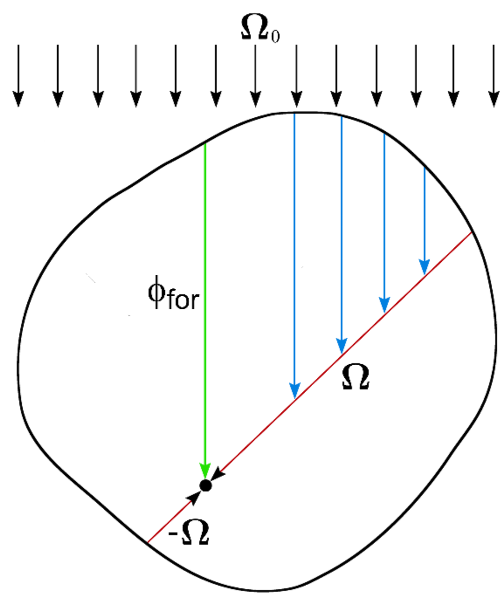


3DHZETRN Formalism

- Plot shows neutron production cross section for 500 MeV protons on aluminum
  - Forward (for) component extends up to high energies
  - Isotropic (iso) component associated with lower energy knockout and evaporation processes

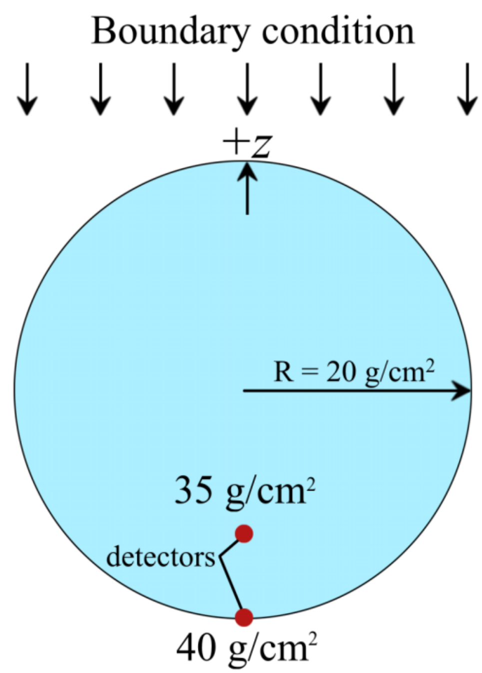


- Plot shows finite geometry with boundary condition directed along Ω_0
  - Forward solution at target point and at points along stream direction, Ω, obtained within straight ahead approximation
  - Discrete number of Ω directions (streams) chosen to represent isotropic field



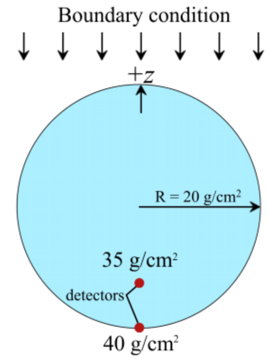
Verification: Sphere benchmark (I)

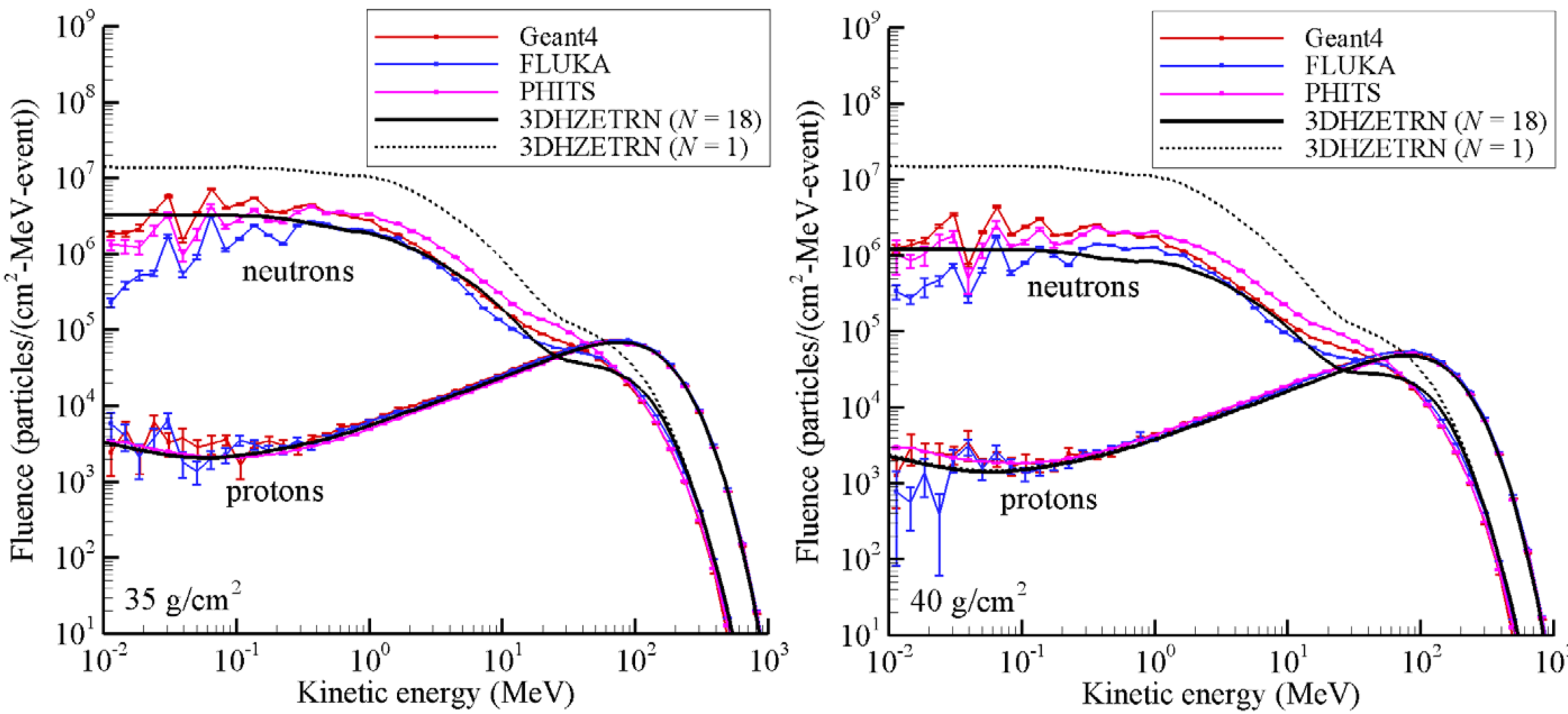
- First benchmark is for a sphere of aluminum (radius 20 g/cm^2) with external boundary condition applied uniformly down onto sphere along z-axis
  - 1956 Webber SPE spectrum
  - Solar minimum GCR ions: Z = 1, 2, 6, 26
- Convergence testing performed with *N* (number of streams)
  - Reasonable convergence met after *N* = 18



Benchmark: Webber SPE

- Fluctuations in MC results associated with ENDF elastic resonances
- 3DHZETRN (*N*=18) significant improvement over straight-ahead approximation (*N*=1)

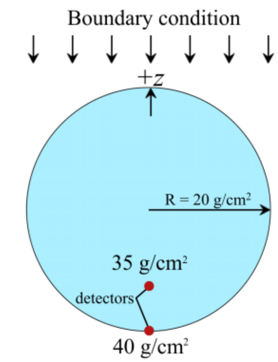


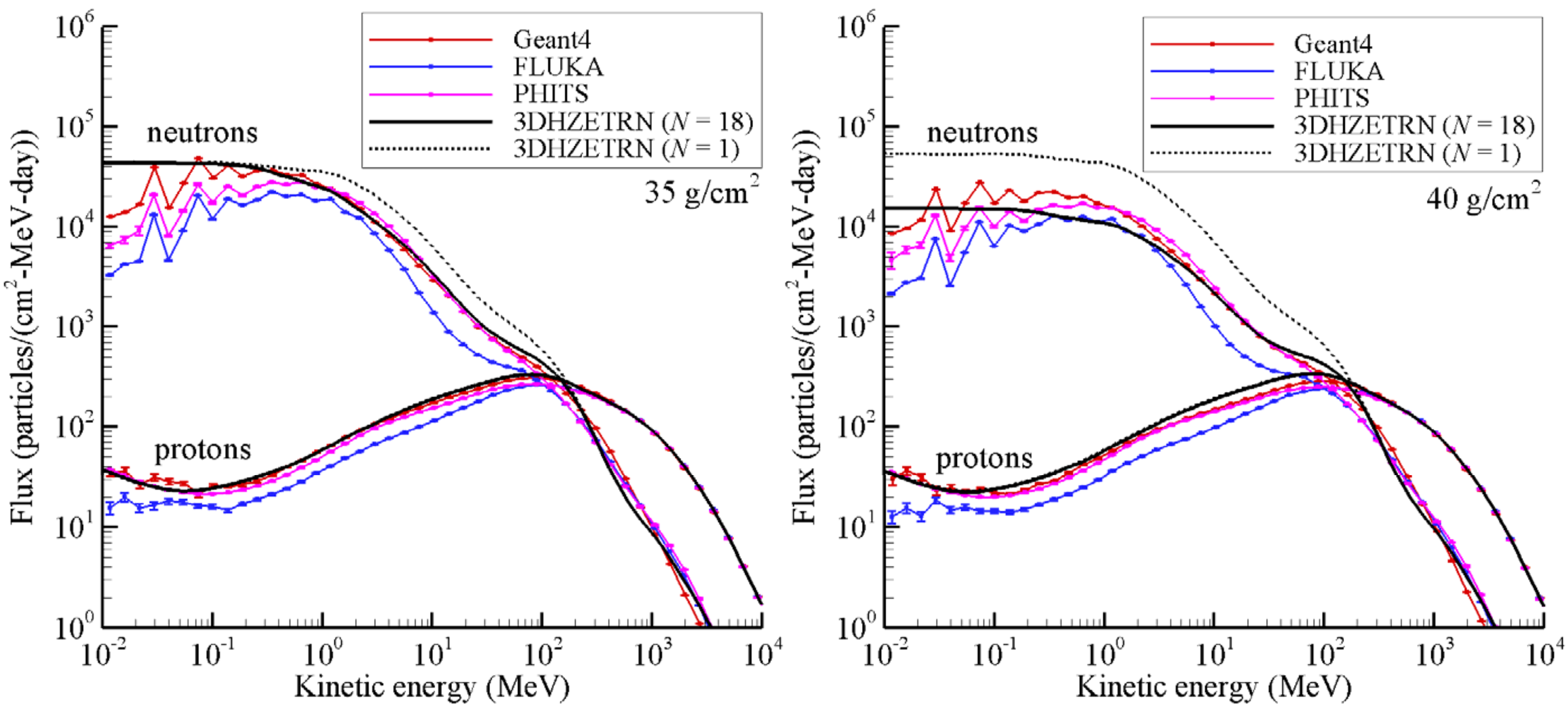


1956 Webber SPE boundary condition

Benchmark: GCR hydrogen

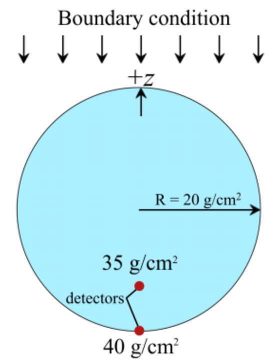
- Good agreement amongst codes for secondary neutrons



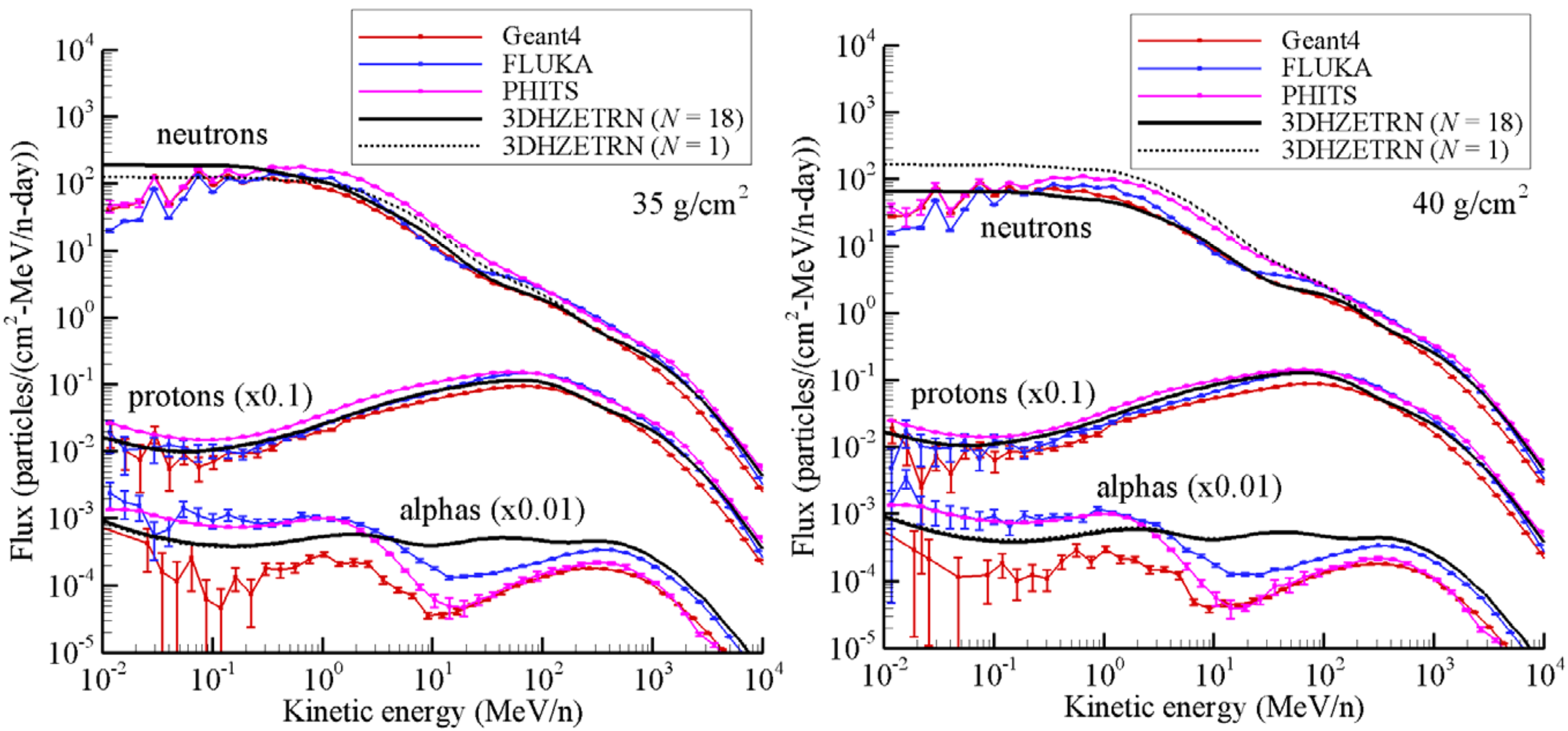


1977 solar min GCR hydrogen boundary condition

Benchmark: GCR iron



- Good agreement amongst codes for secondary nucleons
- Some disagreement in secondary alphas – driven by nuclear cross section models, not transport approximations

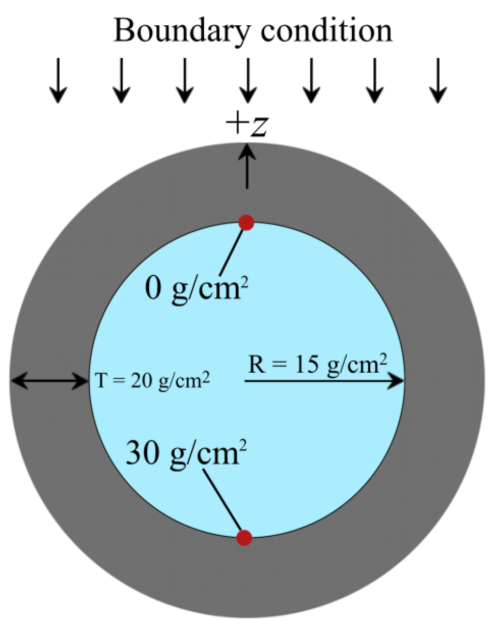


1977 solar min GCR iron boundary condition

Verification: Sphere benchmark (II)

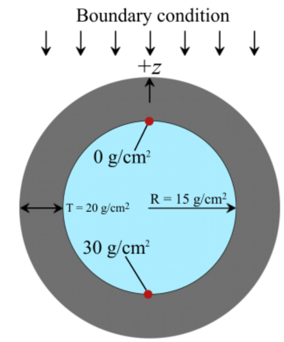
- Next benchmark is for a sphere of ICRU tissue (radius 15 g/cm^2) surrounded by 20 g/cm^2 thick aluminum shield with external boundary condition applied uniformly down onto sphere along z-axis
  - 1956 Webber SPE spectrum
  - Solar minimum GCR ions: Z = 1, 2, 6, 26

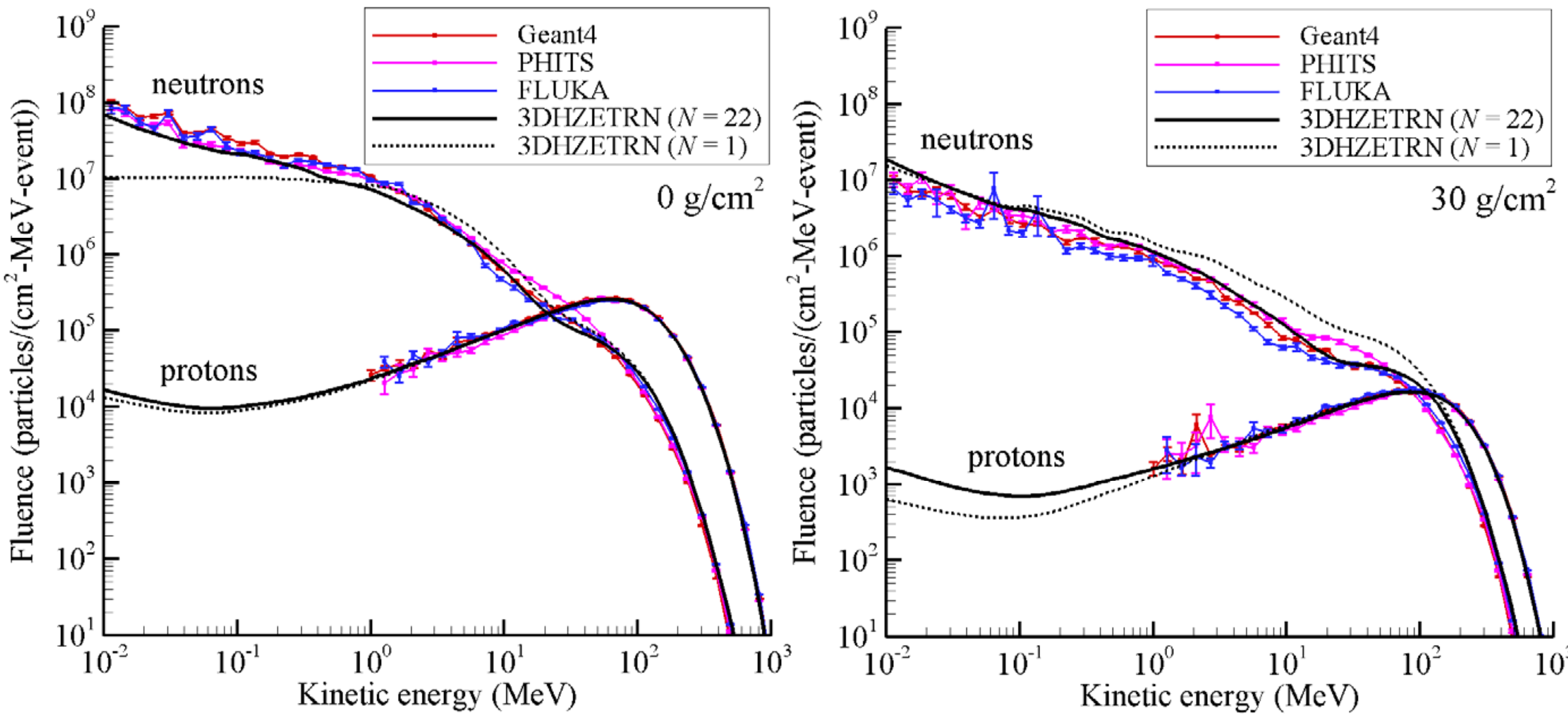
- Convergence testing performed with *N* (number of streams)
  - Reasonable convergence met after *N* = 22



Benchmark: Webber SPE

- Straight-ahead approximation has incorrect neutron spectral shape
- 3DHZETRN (N=22) in close agreement with MC

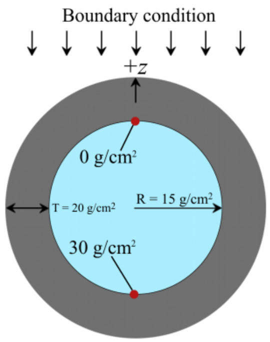


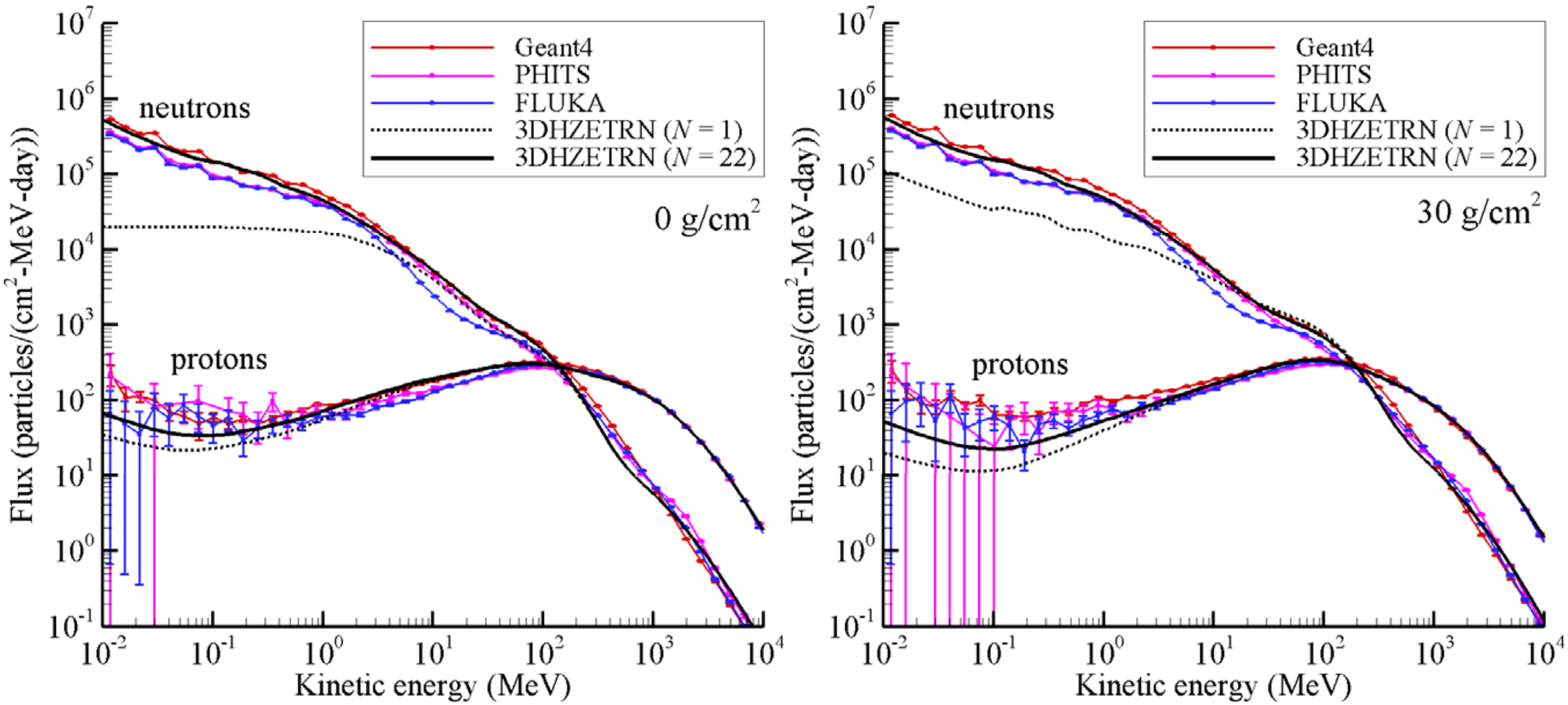


1956 Webber SPE boundary condition

Benchmark: GCR hydrogen

- 3DHZETRN (N=22) in close agreement with MC

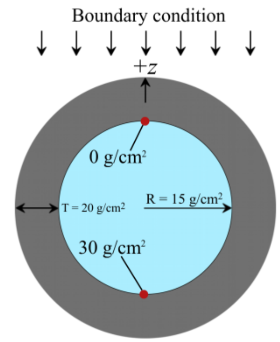


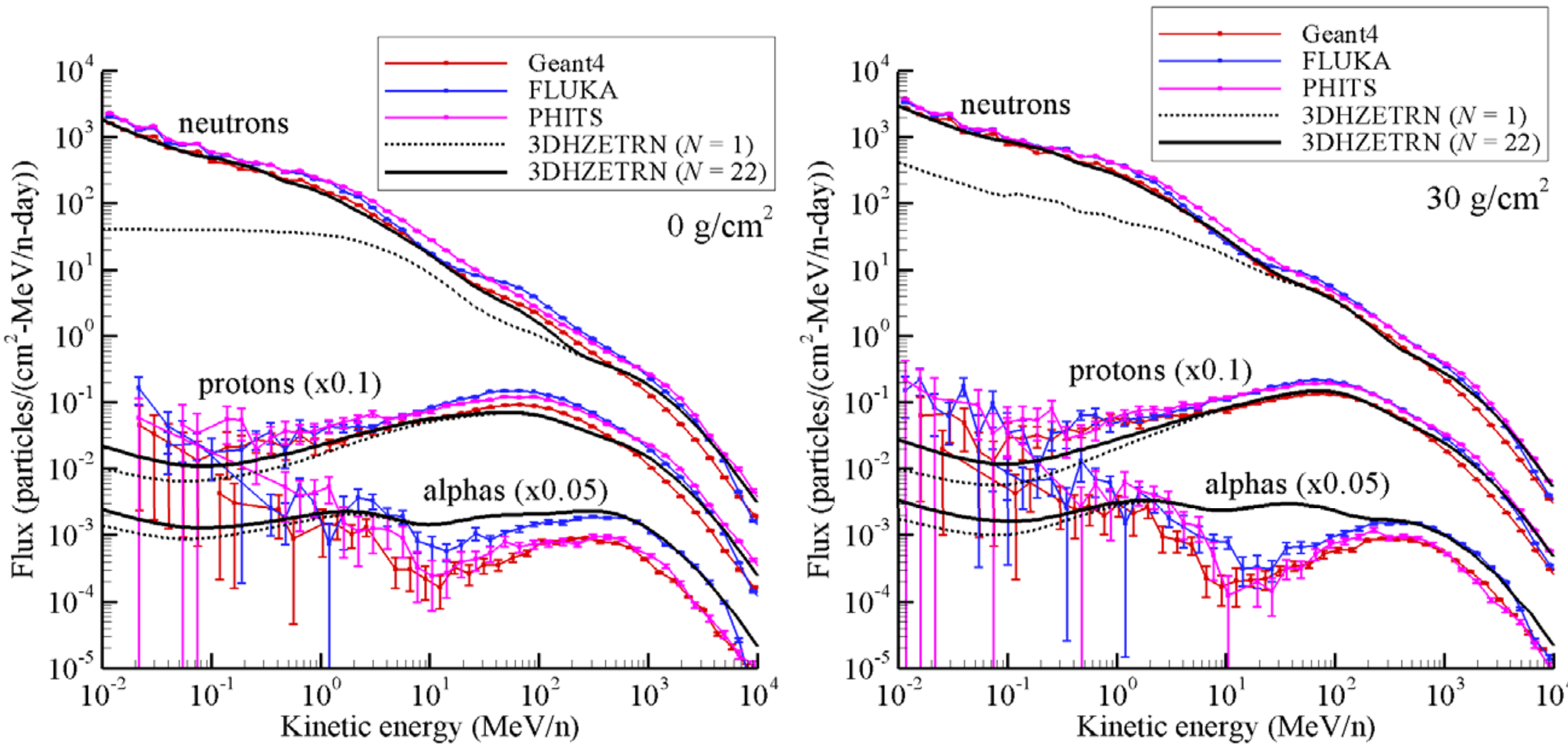


1977 solar min GCR hydrogen boundary condition

Benchmark: GCR iron

- 3DHZETRN (N=22) in close agreement with MC for secondary nucleons
- Differences in secondary alphas driven by nuclear cross section models





1977 solar min GCR iron boundary condition

Summary and Future Work

- Newly developed 3DHZETRN code includes 3D corrections for neutrons and neutron-induced light ions
- Benchmark comparisons with MC codes showed significant improvement in 3DHZETRN results and close agreement for nucleons
  - Non-trivial differences in nuclear physics models still present
- Current code can work from limited set of combinatorial geometries (currently extending)
- Extend to engineering ray trace representation of complex geometries
  - Connects to current methodologies used for vehicle design and shield optimization
- Extend to 3D light ion/neutron using isotropic/straight-ahead interaction
- Begin space flight validation

Publications

- Journal publications

Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., 3DHZETRN: Neutron Leakage in Finite Objects. Life Sciences in Space Research, under review (2014).

Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., 3DHZETRN: Shielded ICRU Spherical Phantom. Life Sciences in Space Research, submitted (2014).

Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., Advances in NASA Radiation Transport Research: 3DHZETRN. Life Sciences in Space Research, Volume 2, pp. 6-22 (2014).

- NASA Reports

Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., A Study of Neutron Leakage in Finite Objects, NASA Technical Paper, under review (2014).

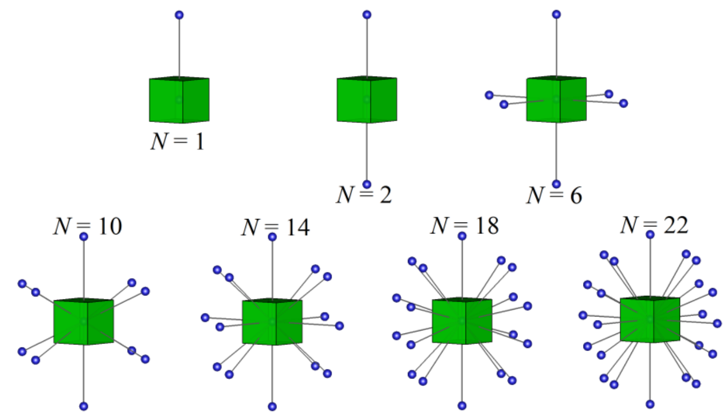
Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., 3D Space Radiation Transport in a Shielded ICRU Tissue Sphere, NASA Technical Paper 2014-218530 (2014).

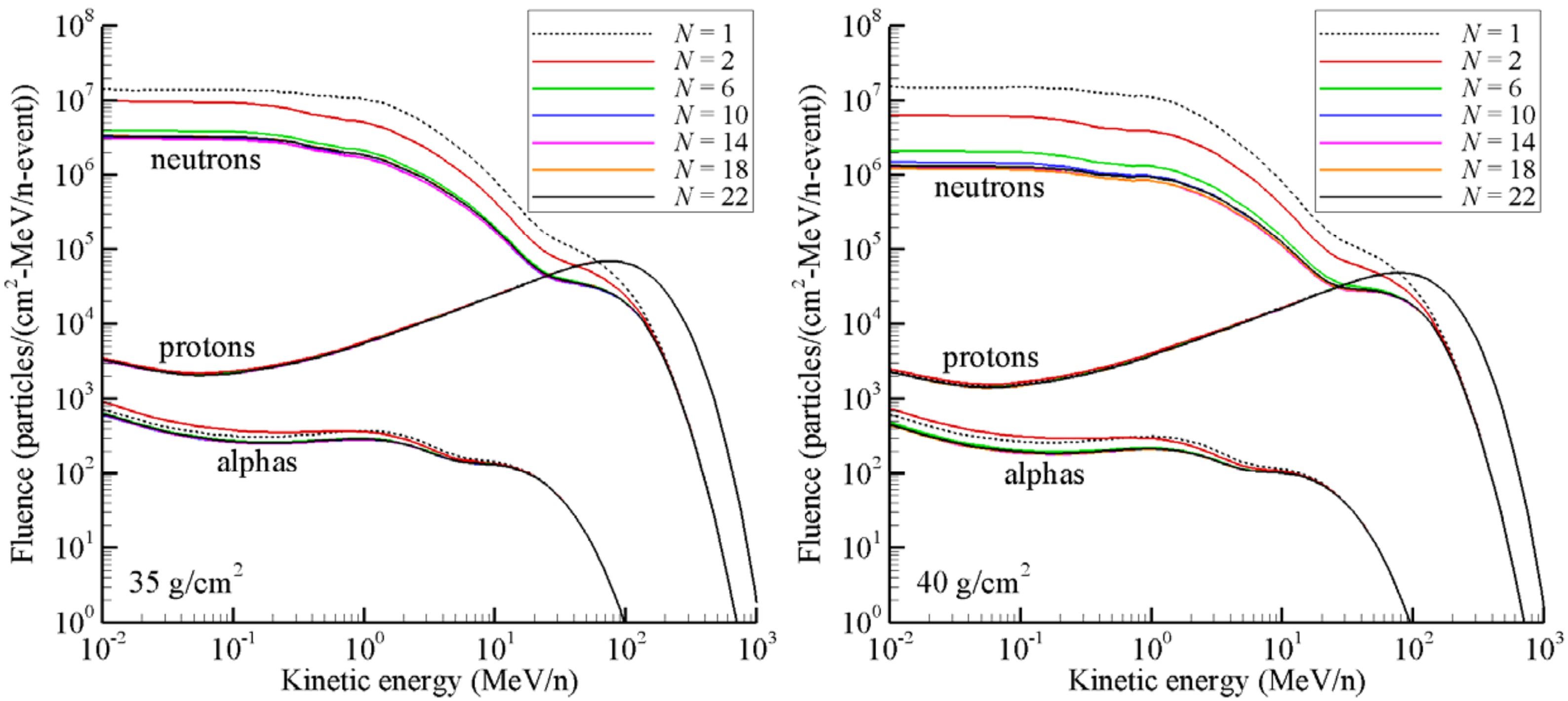
Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., A 3DHZETRN Code in a Spherical Uniform Sphere with Monte Carlo Verification, NASA Technical Paper 2014-218271 (2014).

Backup

Convergence Testing (I)

- Image at right shows the ray-distributions used to evaluate isotropic particle field
- Plot below shows nucleon and alpha fluences induced by Webber SPE in benchmark geometry
- N=18 and N=22 are clearly converged

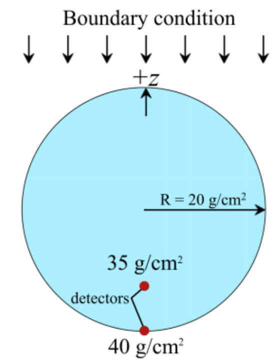


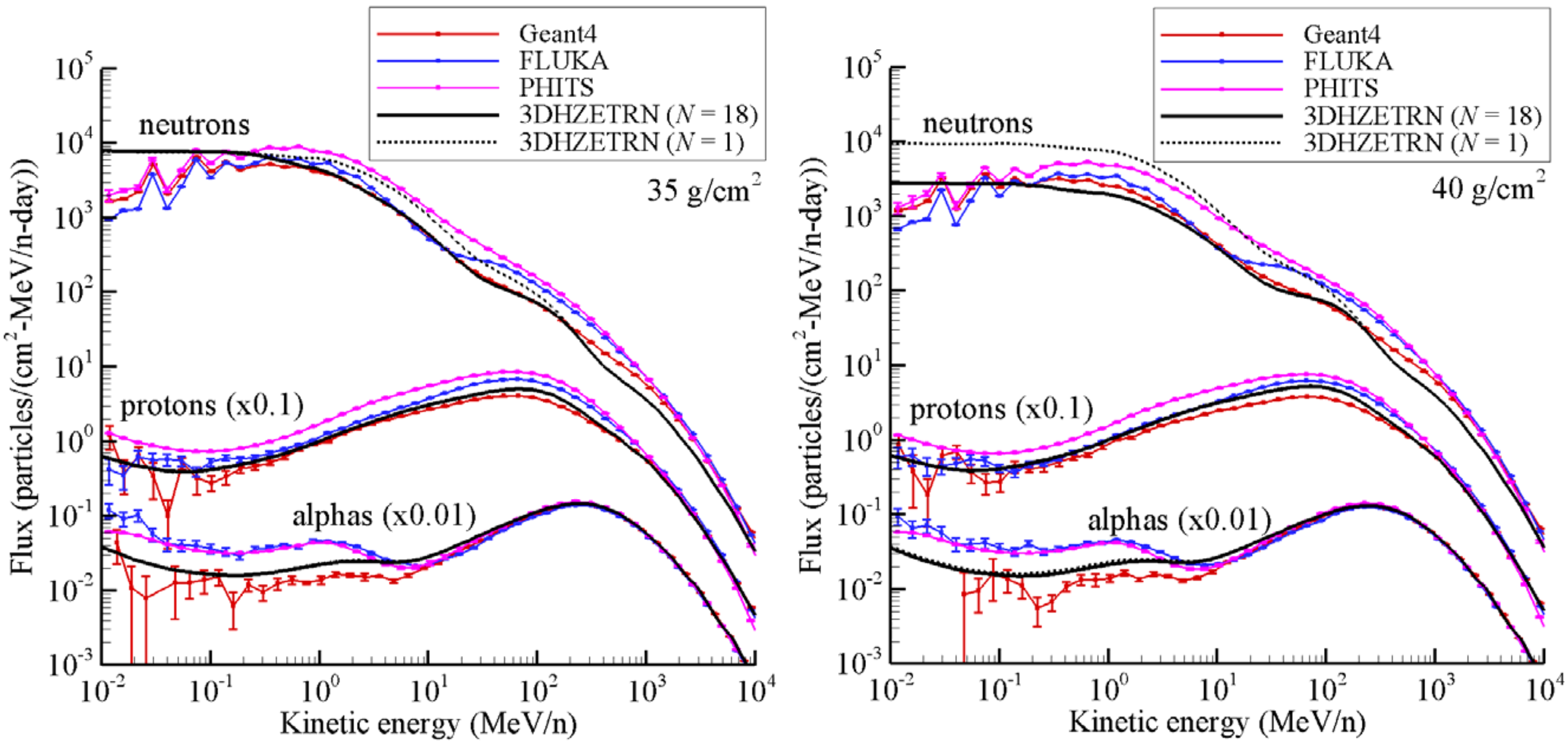


1956 Webber SPE boundary condition

Benchmark: GCR alpha (I)

- Good agreement amongst codes for primary alphas and secondary nucleons

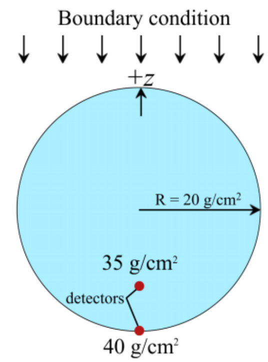


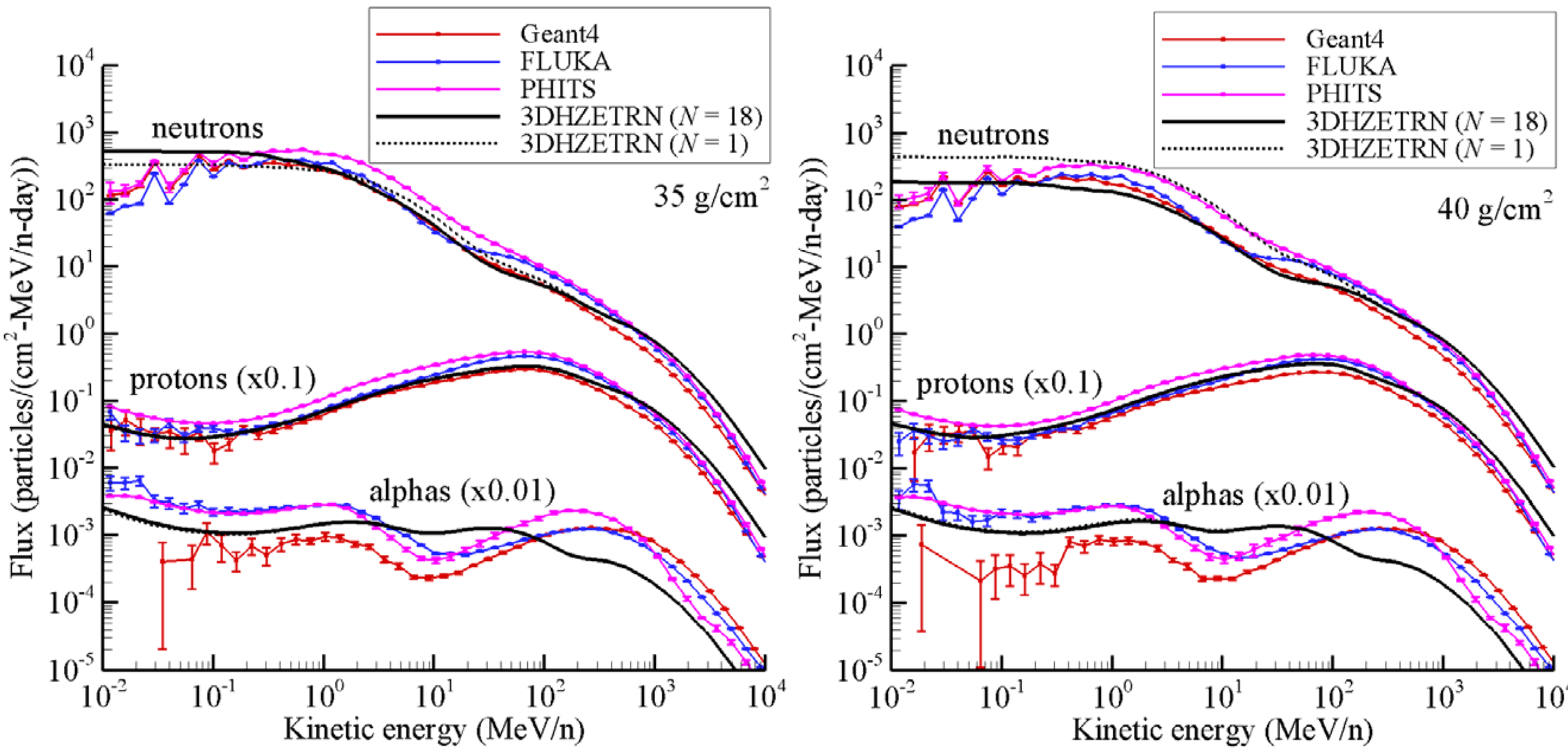


1977 solar min GCR alpha boundary condition

Benchmark: GCR carbon (I)

- Good agreement amongst codes for secondary nucleons
- Some disagreement in secondary alphas – driven by nuclear cross section models, not transport approximations

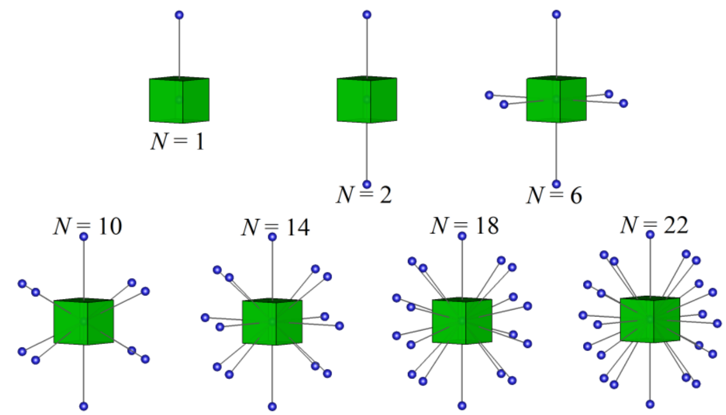


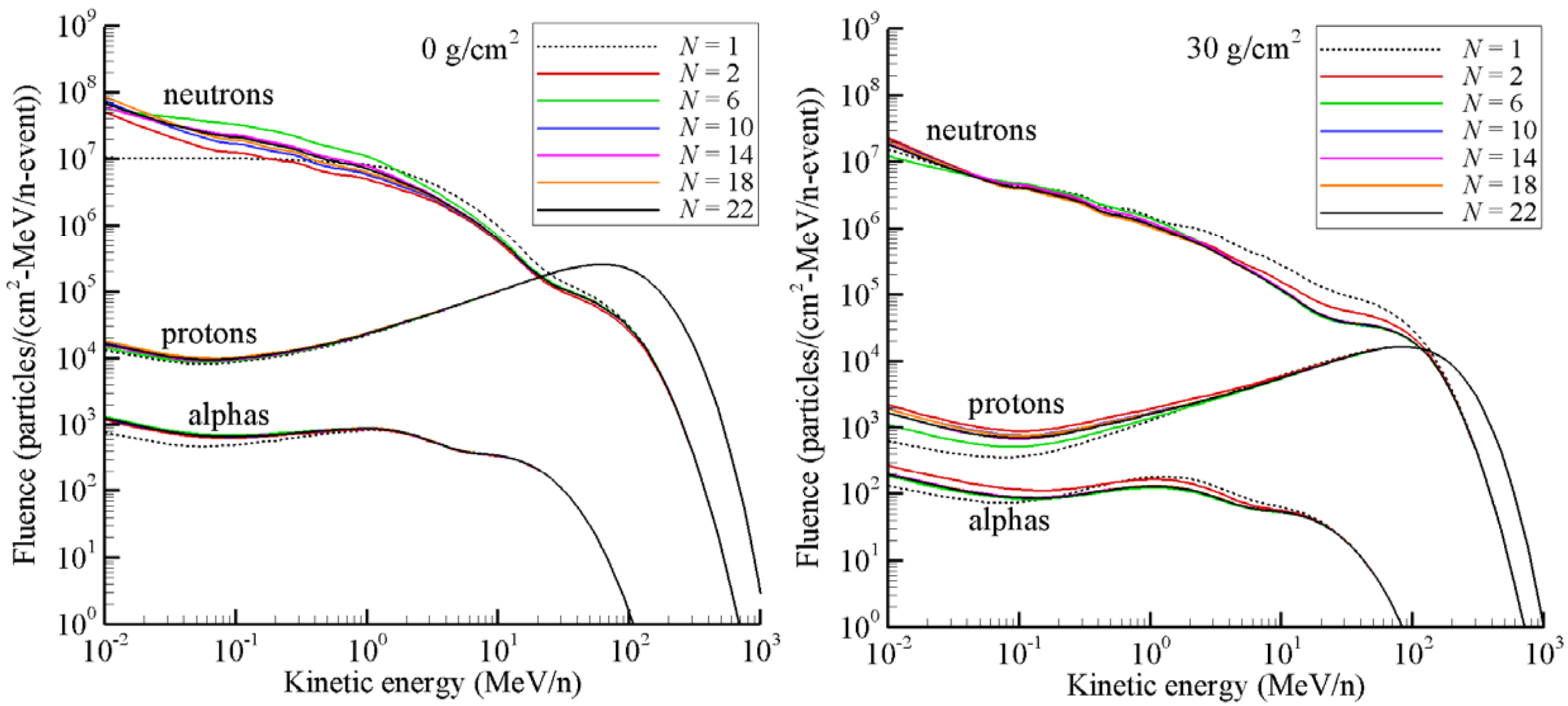


1977 solar min GCR carbon boundary condition

Convergence Testing (II)

- Image at right shows the ray-distributions used to evaluate isotropic particle field
- Plot below shows nucleon and alpha fluences induced by Webber SPE in benchmark geometry
- N=18 and N=22 are clearly converged
- N=1 gives incorrect spectral shape





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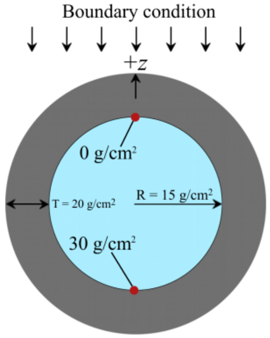
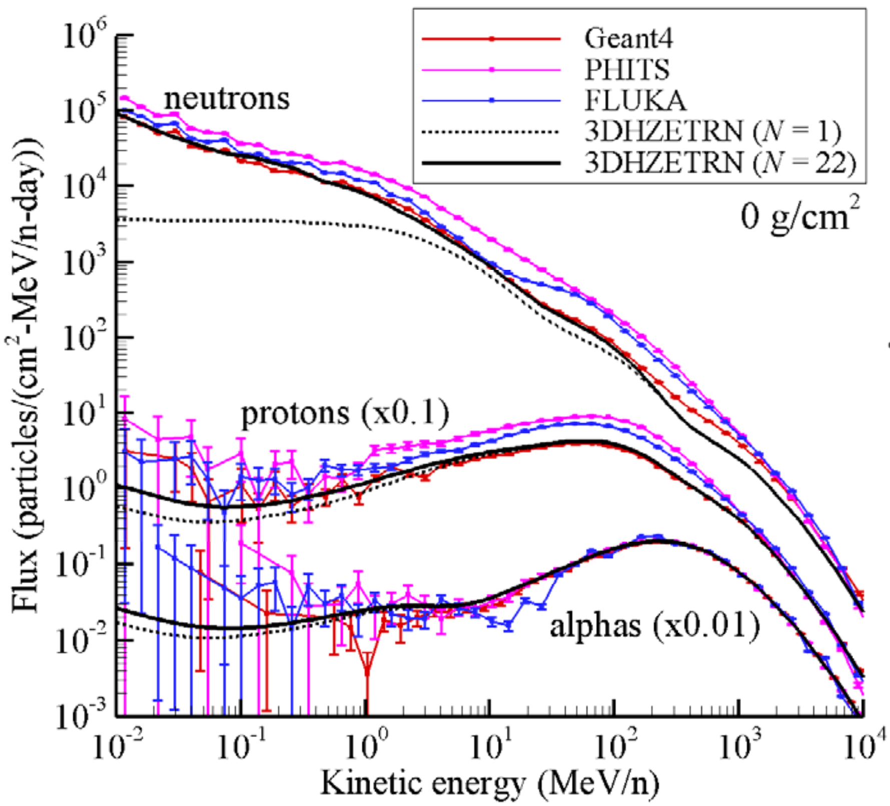
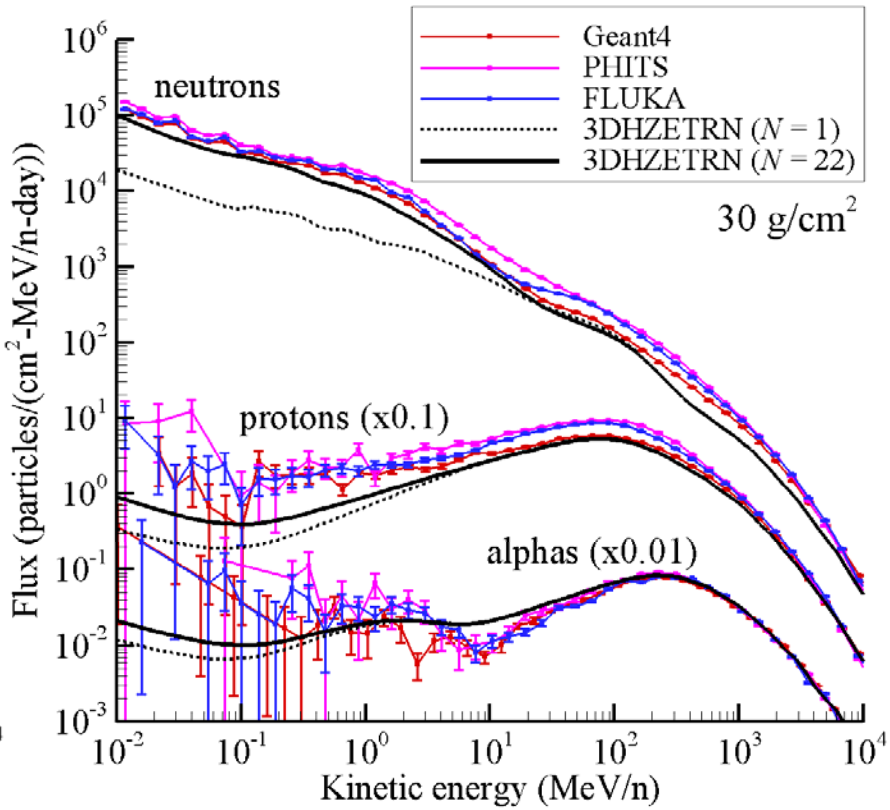
Benchmark: GCR alpha (II)

- 3DHZETRN (N=22) in close agreement with MC for secondary nucleons and primary alphas







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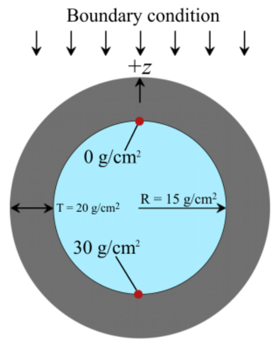
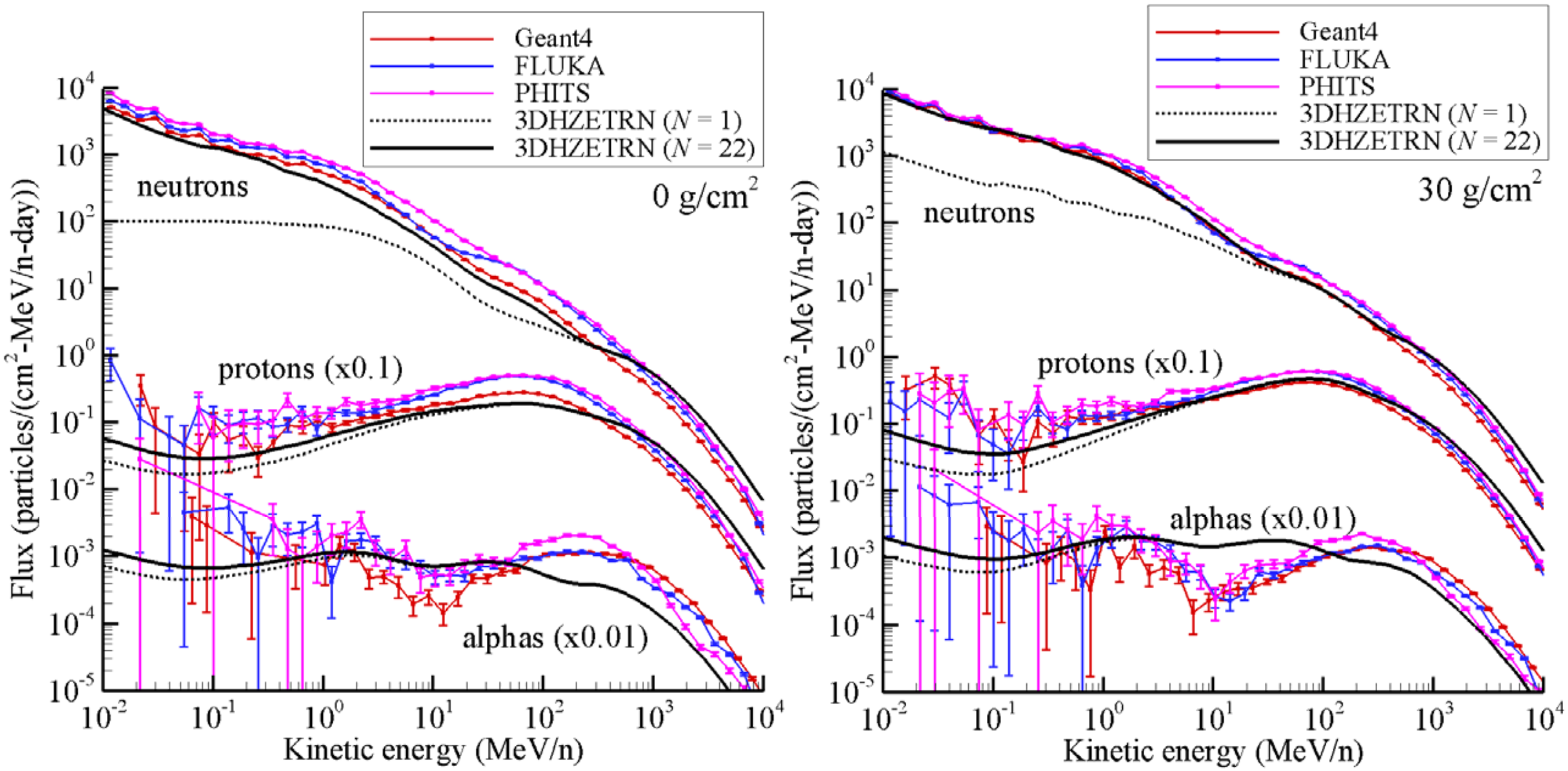
Benchmark: GCR carbon (II)

- 3DHZETRN (N=22) in close agreement with MC for secondary nucleons
- Differences in secondary alphas driven by nuclear cross section models





1977 solar min GCR carbon boundary condition