Particle spectra on the Martian surface – An update on the comparison of models and MSL-RAD measurements

Daniel Matthiä[1], Bent Ehresmann[2], Henning Lohf[3], Jan Köhler[3], Cary Zeitlin[4] Jan Appel[3], Tatsuhiko Sato[5], Tony Slaba[6], Cesar Martin[3], Thomas Berger[1], Eckart Boehm[3], Stephan Boettcher[3], David E. Brinza[7], Soenke Burmeister[3], Jingnan Guo[3], Donald M. Hassler[2], Arik Posner[8], Scot C. R. Rafkin[2], Günther Reitz[1], John W. Wilson[9], and Robert F. Wimmer-Schweingruber[3]

[1]German Aerospace Center, Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany

[2]Southwest Research Institute, Space Science and Engineering Division, Boulder, USA

[3]Institute of Experimental and Applied Physics, Christian-Albrechts-University, Kiel, Germany

[4]Southwest Research Institute, Space Science and Engineering Division Durham, NH, USA

[5]Japan Atomic Energy Agency, Tokai, Iberaki, Japan

[6]NASA Langley Research Center, 2 West Reid St., MS 188E, Hampton, VA 23681, USA

[7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

[8]NASA Headquarters, Washington, DC, USA

[9]Old Dominion University, Norfolk VA 23529 USA

Knowledge for Tomorrow

Overview

- Update on the comparison of the calculated particle fluxes and dose rates with MSL-RAD data (presented last year, now published)
- “1st Mars Space Radiation Modeling Workshop” held in June 2016 in Boulder
- Development of a parameterized radiation model for the Martian atmosphere at DLR

Comparison of models with experimental data

- Motivation:
  - Numerical models can be used as predictive tools for human exploration
  - Validation of numerical models against experimental data is essential
- Goals:
  - Test of different Galactic Cosmic Radiation (GCR) models
  - Validation of different transport models (GEANT4, PHITS, OLTARIS, HZETRN)
  - Particle flux and dose rates on ground
  - Comparison to RAD results

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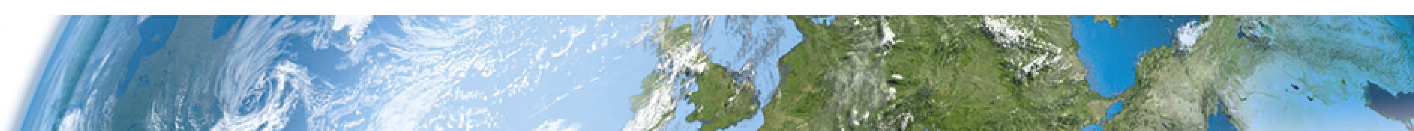
RESEARCH ARTICLE OPEN ACCESS

The Martian surface radiation environment – a comparison of models and MSL/RAD measurements

Daniel Matthiä[1,*], Bent Ehresmann[2], Henning Lohf[3], Jan Köhler[3], Cary Zeitlin[4], Jan Appel[3], Tatsuhiko Sato[5], Tony Slaba[6], Cesar Martin[3], Thomas Berger[1], Eckart Boehm[3], Stephan Boettcher[3], David E. Brinza[7], Soenke Burmeister[3], Jingnan Guo[3], Donald M. Hassler[2], Arik Posner[8], Scot C. R. Rafkin[2], Günther Reitz[1], John W. Wilson[9], and Robert F. Wimmer-Schweingruber[3]

[1] German Aerospace Center, Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany
[*]Corresponding author: Daniel.Matthiae@dlr.de
[2] Southwest Research Institute, Space Science and Engineering Division, Boulder, CO 80302, USA
[3] Institute of Experimental and Applied Physics, Christian-Albrechts-University, 24118 Kiel, Germany
[4] Southwest Research Institute, Space Science and Engineering Division, Durham, NH 03824, USA
[5] Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[6] NASA Langley Research Center, 2 West Reid St., MS 188E, Hampton, VA 23681, USA
[7] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[8] NASA Headquarters, Washington, DC 20546, USA
[9] Old Dominion University, Norfolk, VA 23529, USA



The setup for the simulations

- **Atmosphere:**
  - 22 g/cm^2
  - Composition (mass %): 95.7% CO_2, 2.7% N,1.6% Ar (Mars-Gram 2001)
- **Soil:** ≥20m, composition from OLTARIS

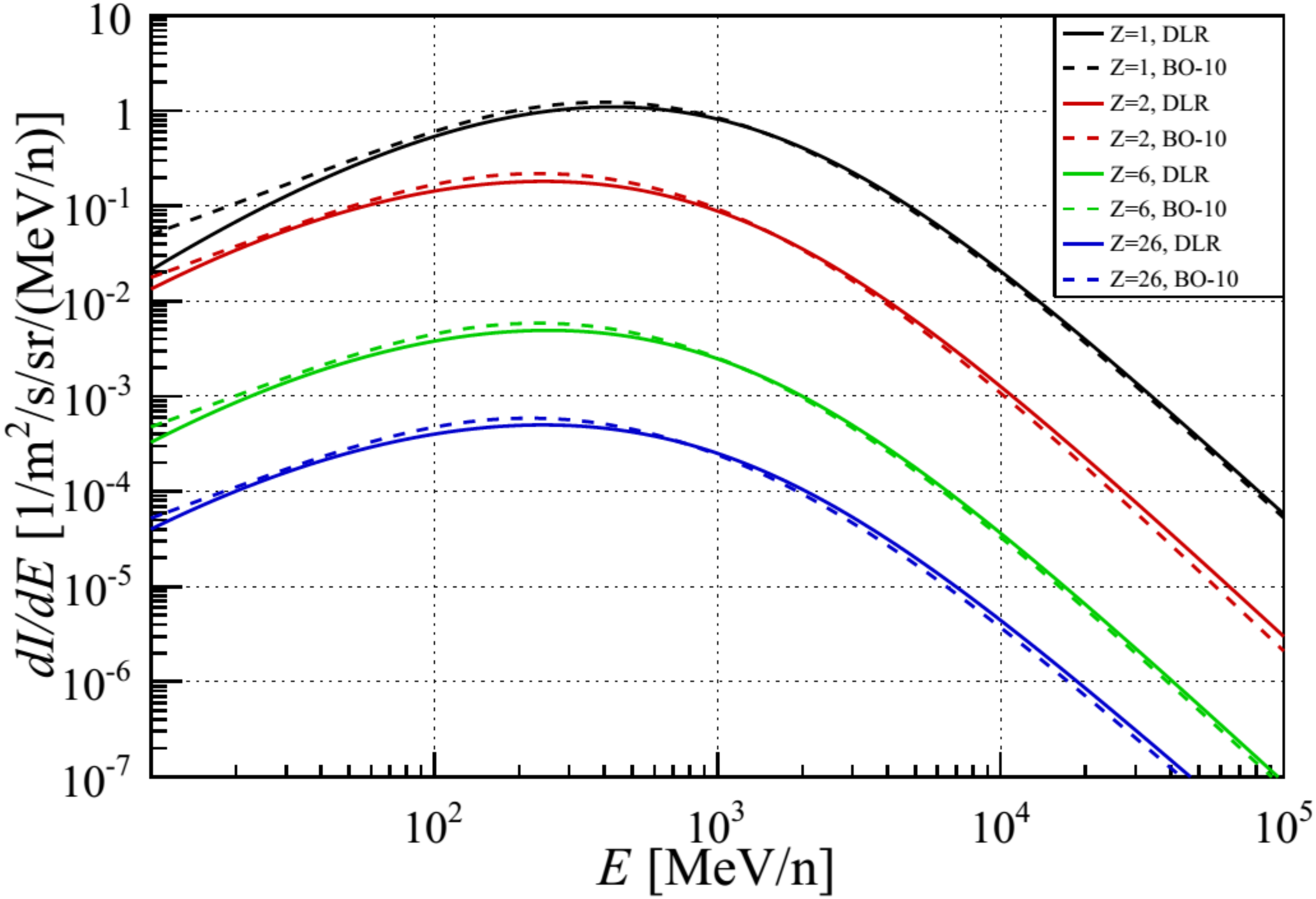
Density: 1.7 g/cm^3

Defined in Terms of Molecular Percentages	
Formula	**Percentage(0 < p <= 100)**
O_2Si	51.2
Fe_2O_3	9.3
$Al_2CaK_2MgNa_2O_7$	32.1
H_2O	7.4
Total	**100.0**

- **GCR-Input:** DLR and Badhwar/O'Neill 2010:
  - 19. Aug. 2012 (doy 232, 2012) until 17. Feb. 2013 (doy 48, 2013), 182 days
- **Particles: neutron** (10^{-8} MeV to 10^4MeV), **proton** (1MeV to 10^5MeV), **gamma** (10^{-3}MeV to 10^4MeV), **$e^{-,+}$** (10^{-3}MeV to 10^4MeV), **deuteron, triton, ^{3}He, ^{4}He, Li/Be/B, C/N/O, Z=9-13, Z≥14** (all 1MeV/n to 10^5MeV/n)
- 4π, zenith angle < 30°

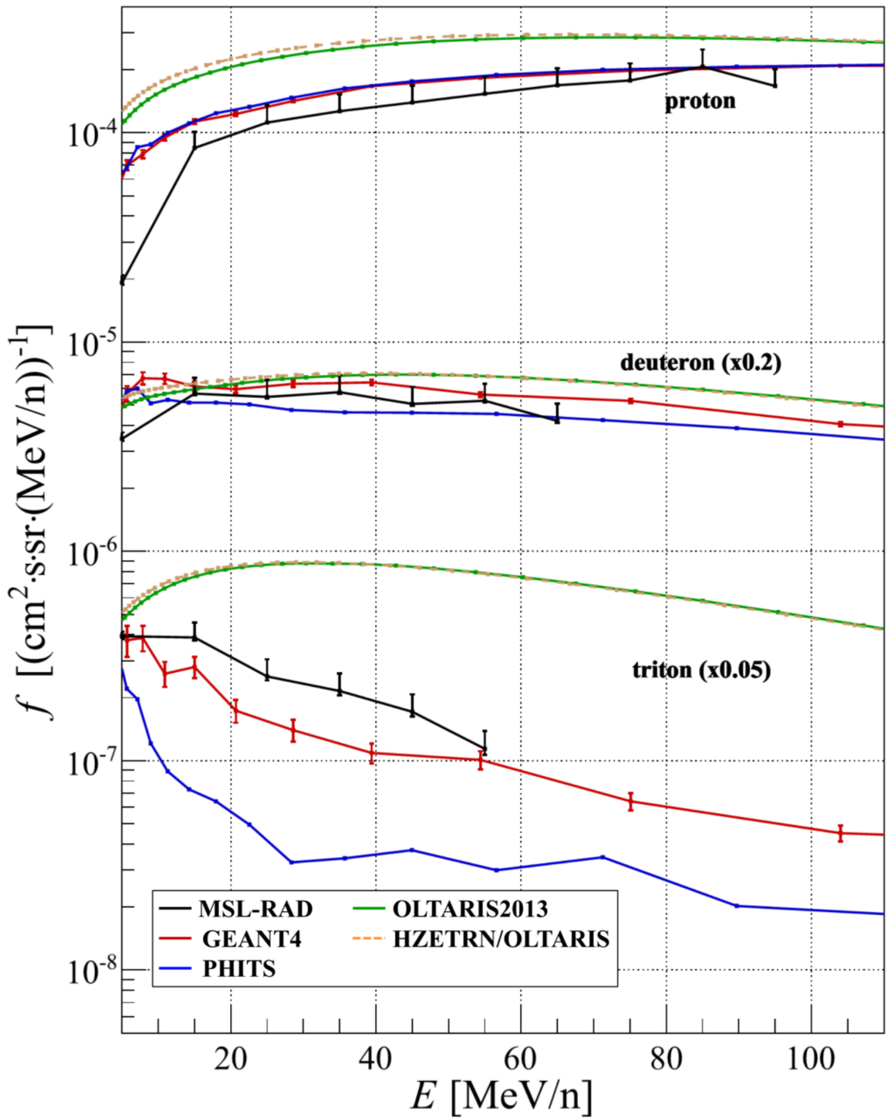
GCR input spectra, DLR and Badhwar/O‘Neill 2010

19. Aug. 2012 (doy 232, 2012) until 17. Feb. 2013 (doy 48, 2013), 182 days



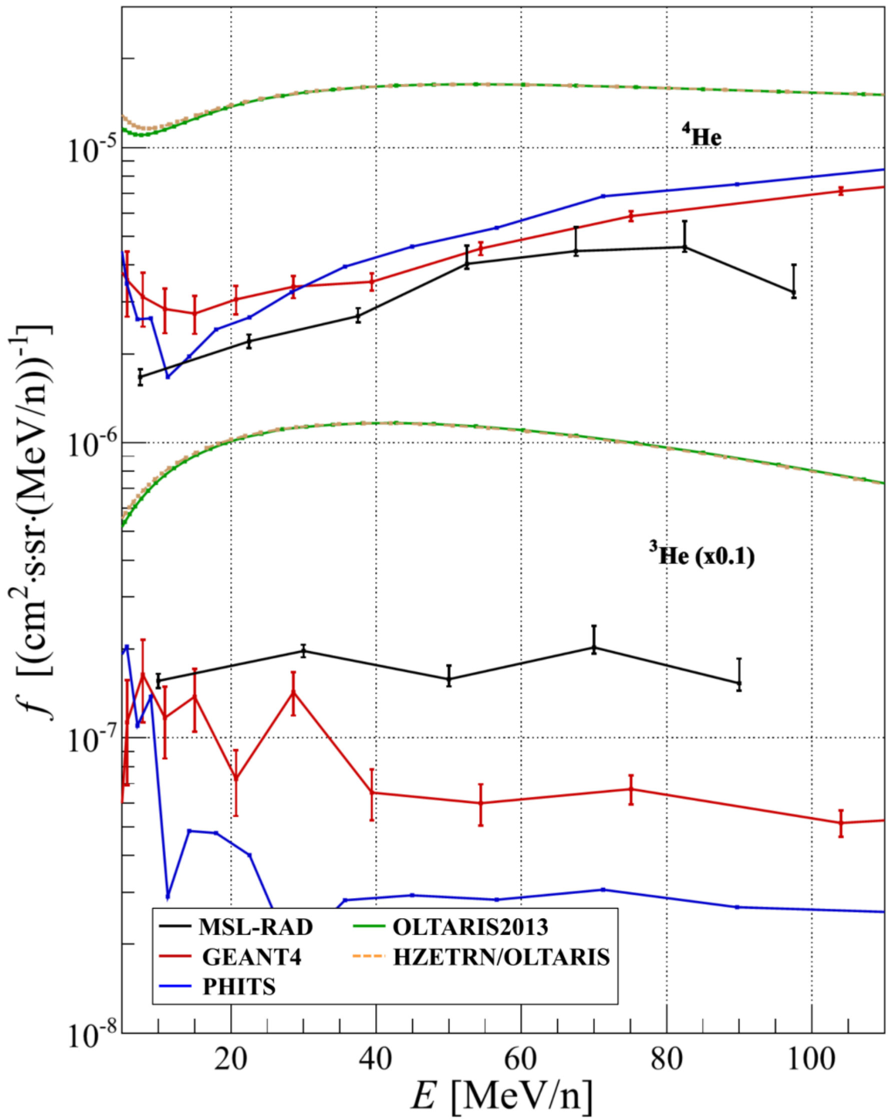
Proton, deuteron, triton

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- **proton:** G4/PHITS best agreement, HZETRN and OLTARIS2013 overestimate
- **deuteron:** all reasonable
- **triton**: G4 good, PHITS underestimates, HZETRN and OLTARIS2013 overestimates
- HZETRN and OLTARIS2013 identical (OLTARIS2013 provided only downward flux)



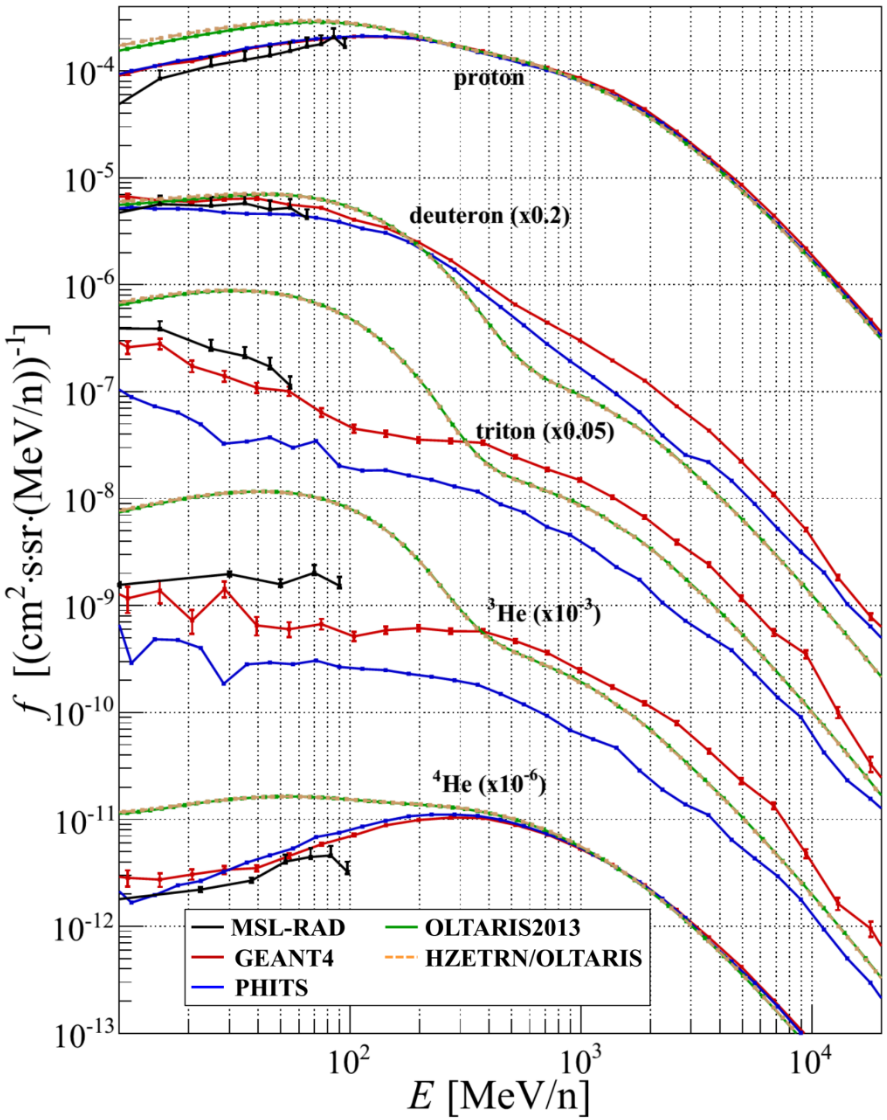
^3He, ^4He

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- ^{3}**He**: G4/PHITS underestimate; HZETRN and OLTARIS2013 overestimate
- ^{4}**He**: G4 good, PHITS slightly overestimates; HZETRN and OLTARIS2013 overestimate



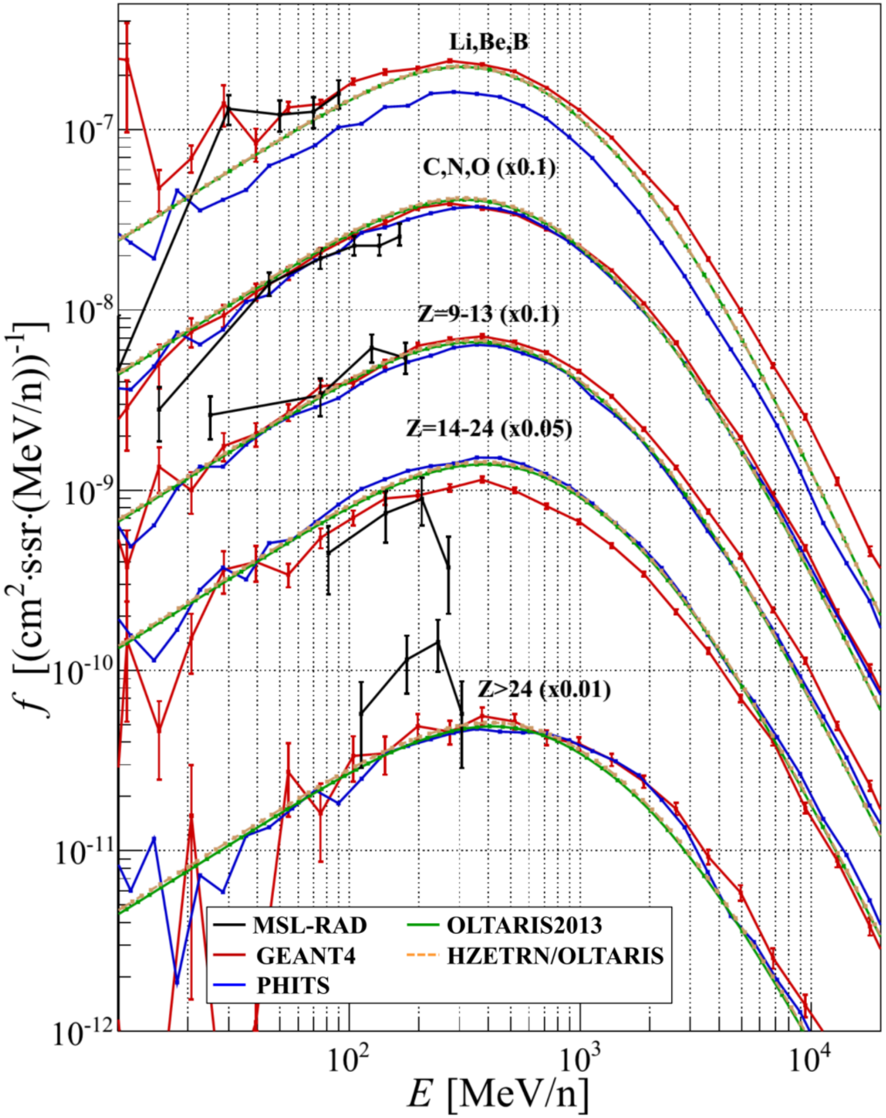
Proton, deuteron, triton, ^{3}He, ^{4}He

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS



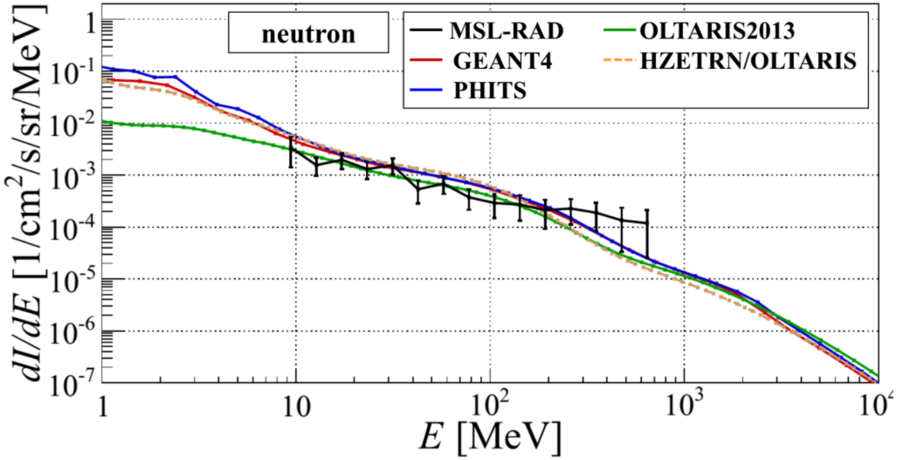
Li/Be/B, C/N/O, Z=9-13, Z=14-24, Z≥25

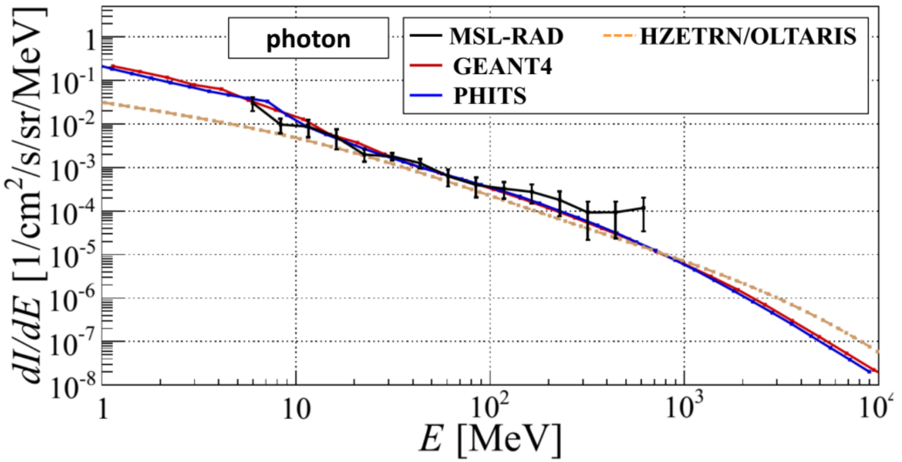
- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- **Li/Be/B:** PHITS underestimates
- **C/N/O, Z=9-13:** agreement reasonable
- **Z=14-24**: G4 good, PHITS, HZETRN and OLTARIS2013 overestimate
- **Z>24**: all underestimate



Neutron and photon

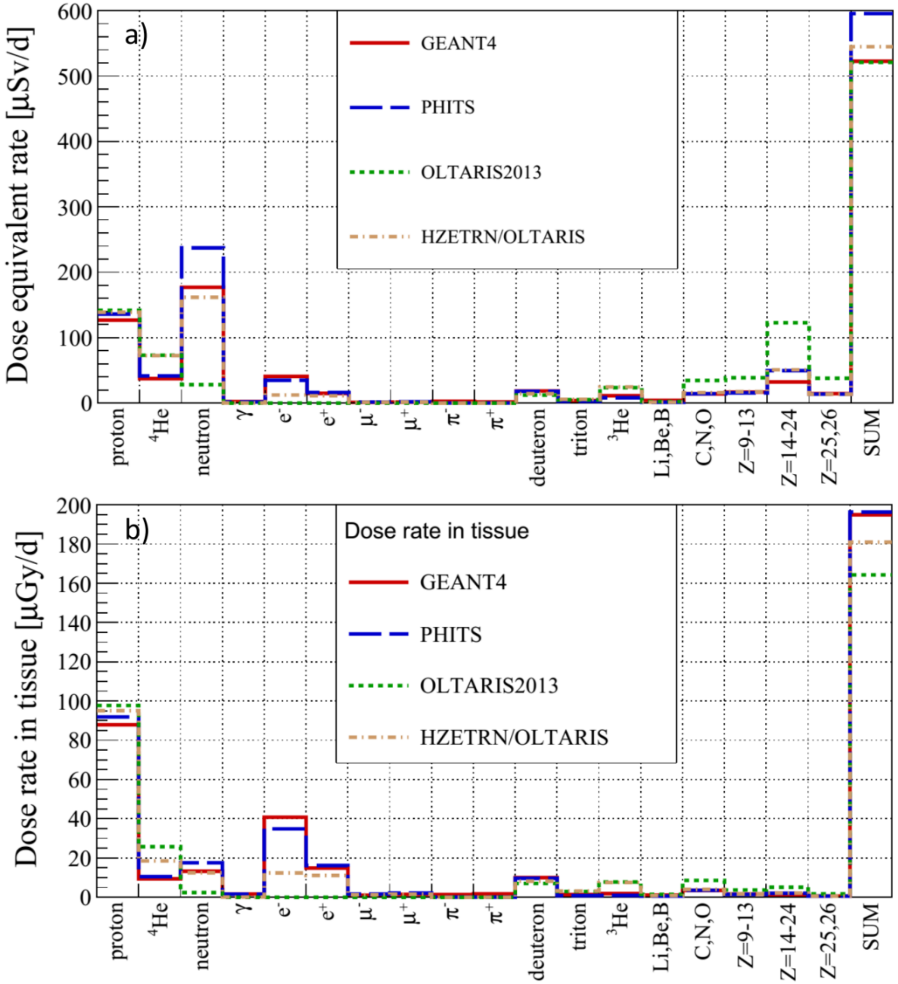
- MSL-RAD data: *Köhler et al. 2014*
- Neutrons (GEANT4, PHITS, HZETRN, OLTARIS2013)
    - Good agreement above 1GeV
    - Lower neutron fluxes from OLTARIS2013 below 1GeV (upward fluxes are missing)
- Photons:
    - Good agreement G4/PHITS
    - HZETRN significantly lower (higher) at energies < 10MeV (>1GeV)





Contribution of different particles to the dose rate

- Very low neutron dose in OLTARIS2013 (no upward flux)
- High neutron dose in PHITS
- Higher dose from high-Z particles in OLTARIS2013
- Agreement of total dose within 10-20%
- MSL-RAD (*Hassler et al. 2014*)
  - 0.21±0.04 mGy/d
  - 0.64±0.12 mSv/d



Comparison of calculated and measured dose rates

Values in parenthesis are the derived quality factors for a restricted zenith angle θ<30°.

	MSL-RAD [Hassler et al., 2014]	GEANT 4.10.p02	PHITS	OLTARIS2013	HZETRN/ OLTARIS
dose rate in tissue [mGy/d]	0.21±0.04	0.19	0.20	0.16	0.18
dose equivalent rate [mSv/d]	0.64±0.12	0.52	0.60	0.52	0.54
Quality factor	**3.05±0.26**	**2.7 (3.0)**	**3.0 (3.4)**	**3.2**	**3.0 (3.2)**

1st Mars Space Radiation Modeling Workshop

- Organised by SWRI, NASA, DLR, CAU
- At SWRI, Boulder, June 28 - 30, 2016
- Goal: Extension of model comparison (new set of experimental data)
- Similar approach as before
- Models:
  - FLUKA (K. Lee, NASA)
  - GEANT4 (D. Matthiä, DLR)
  - GEANT4/HZETRN (A. Firan, R. Rios, NASA)
  - HETC-HEDS (W. de Wet, L. Townsend; Univ. of Tennessee)
  - HZETRN (T. Slaba, NASA)
  - MCNP6 (L. Heilbronn, H. Ratliff, M. Smith; Univ. of Tennessee)
  - PHITS (J. Flores-McLaughlin, NASA)

1st Mars Space Radiation Modeling Workshop, cntd.

- GCR Models: **Badhwar/O'Neill 2014** and **DLR**
  → differences < 10 %

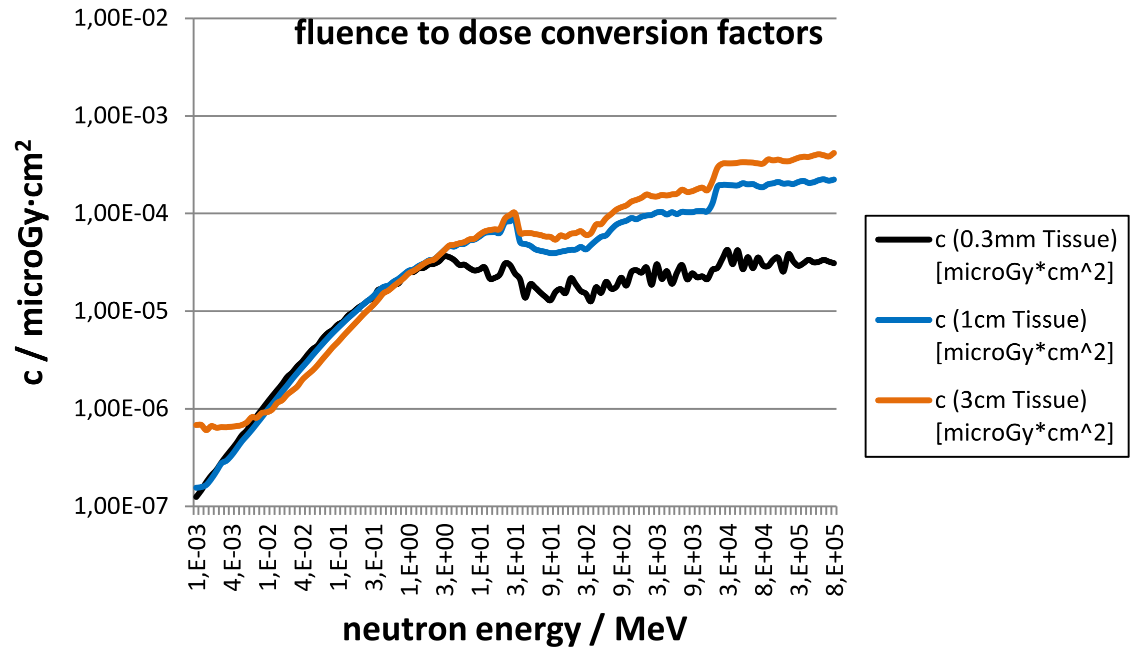
- Large differences between models (orders of magnitude) in particle flux and dose
  - irradiation geometry
  - simulation geometry (atmosphere and detector)
  - particle transport (physics models)
  - normalization
  - dose conversion/calculation

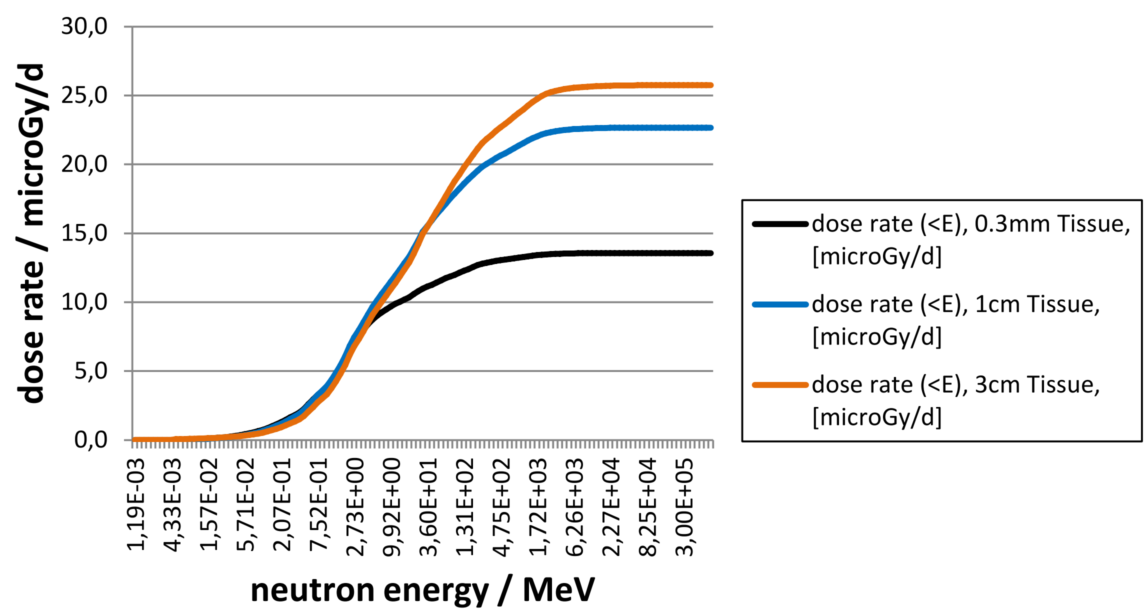
Dose rate for different geometries

- $D = \int dE\ F(E) \cdot c(E)$
- c are fluence to dose conversion factors
- c depends on the geometry
  - material
  - organ / slab / detector
  - thickness
  - …

Neutron spectrum at the Martian surface

→calculated neutron dose rates about 100% higher for 3cm tissue slab

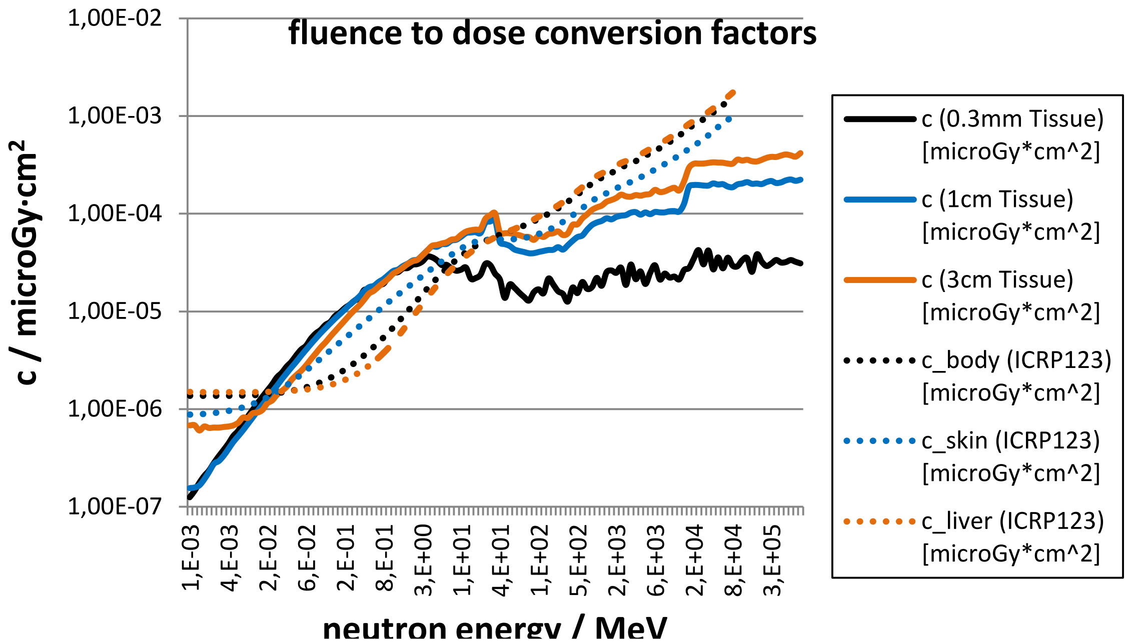


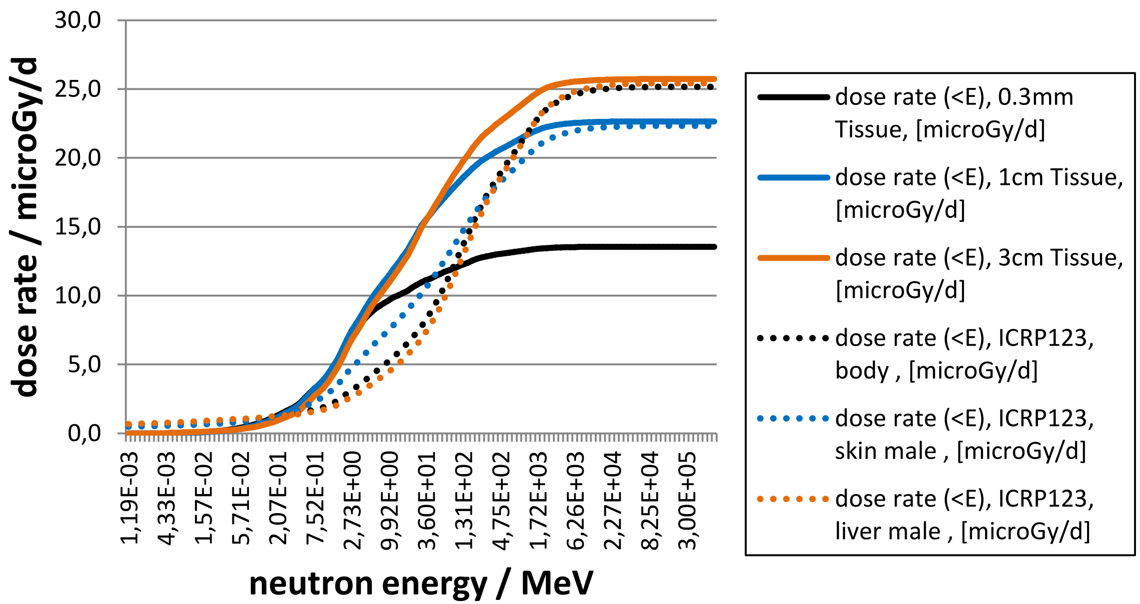


Dose rate for different geometries

→calculated skin dose rate is similar to 1cm tissue slab

→body and liver dose rate is similar to 3cm tissue slab

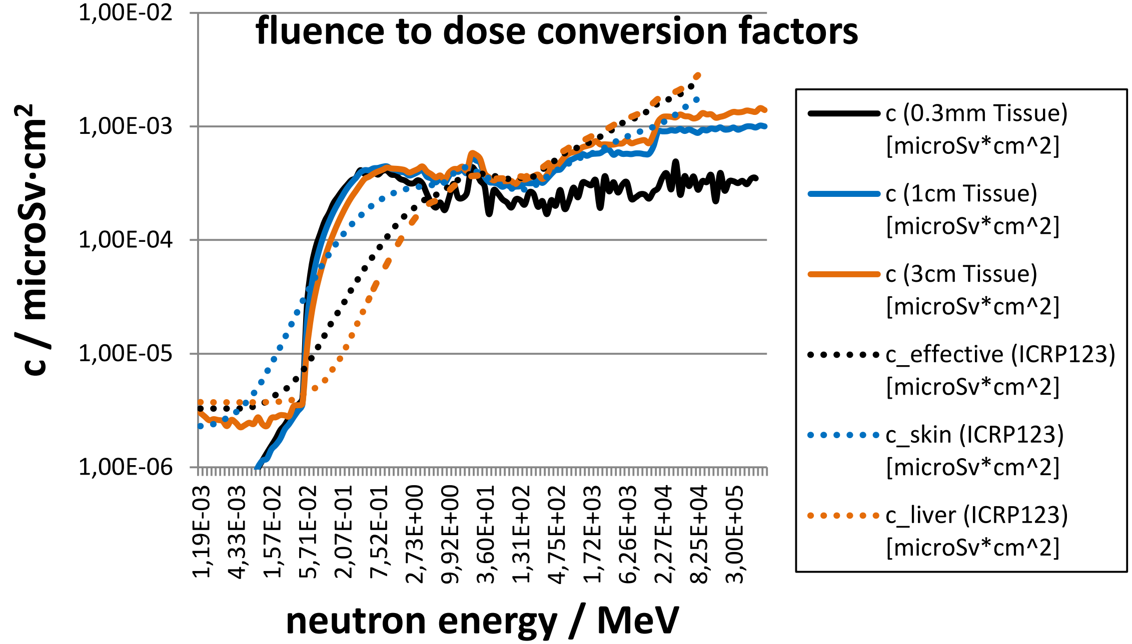


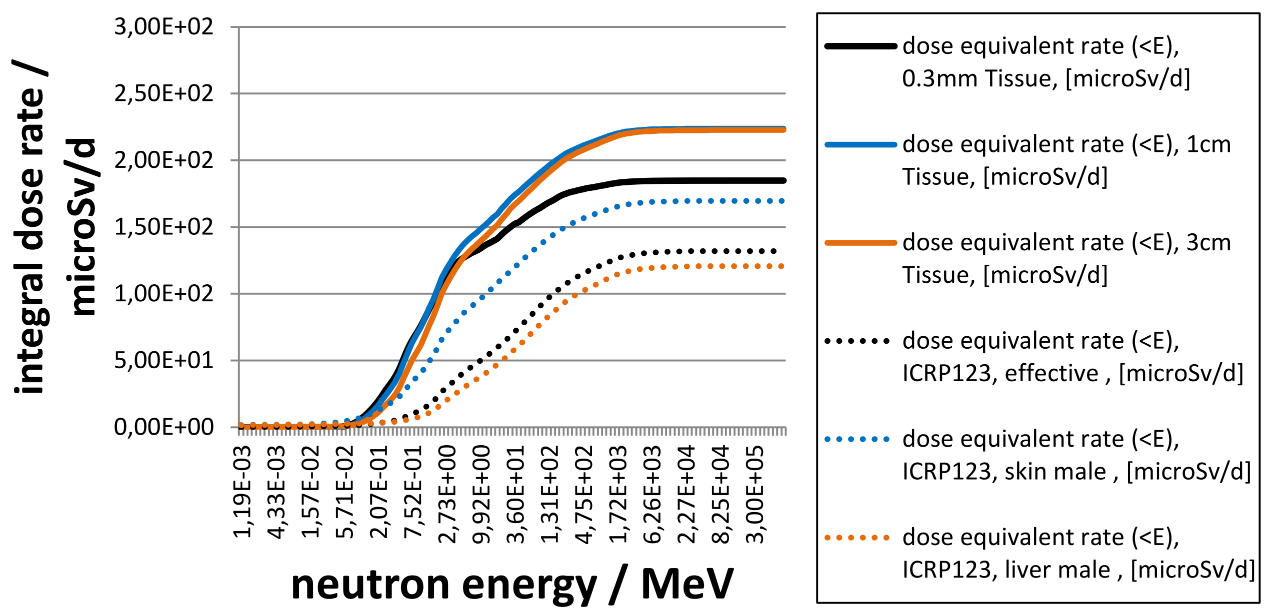


Dose rate for different geometries

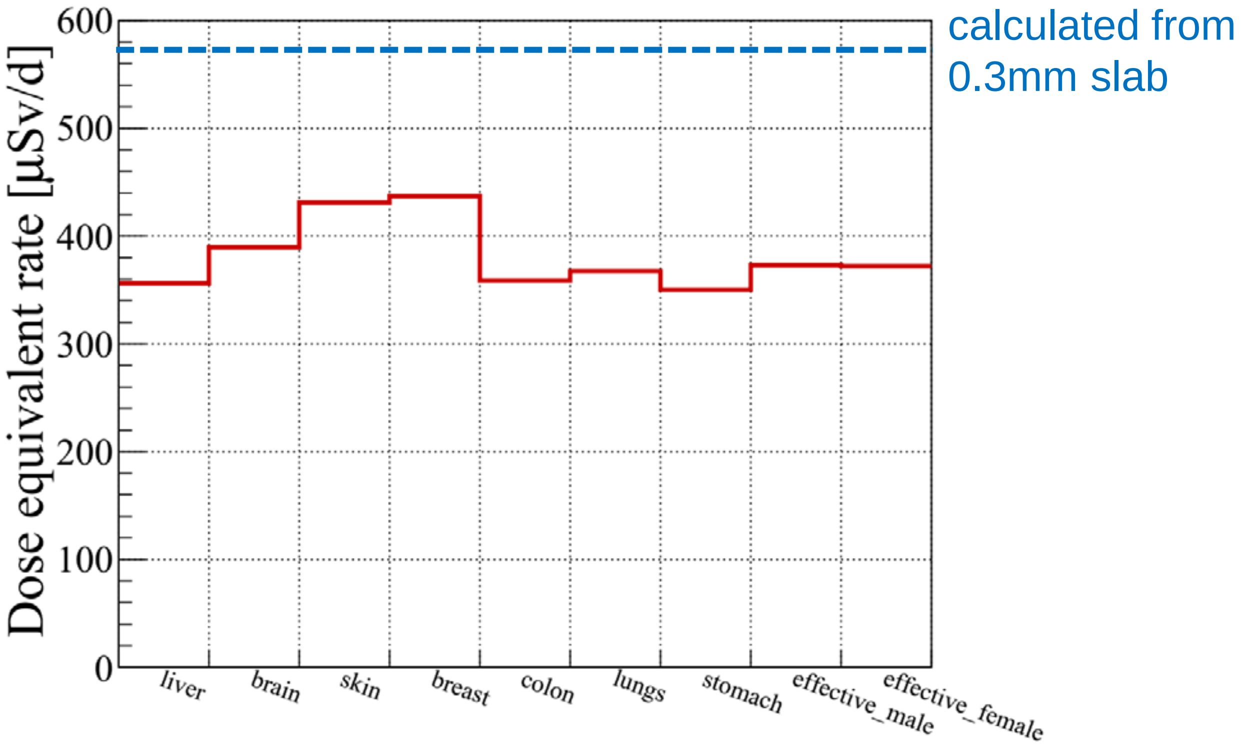
calculated organ dose equivalent rates are lower than slab eq. dose rates!

neutrons below a few MeV are effectively shielded by the body!





Comparison of total organ and slab dose rates



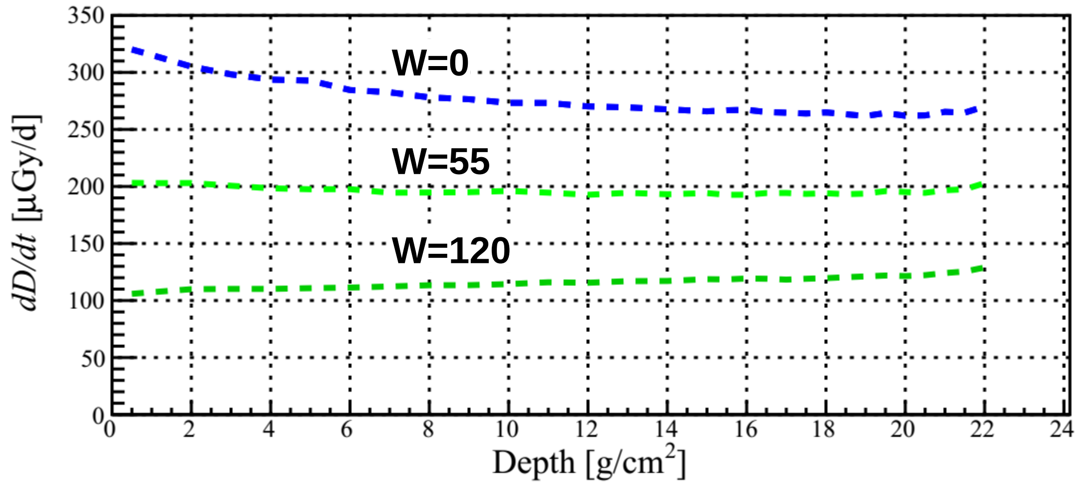
Conclusion: Detector sizes and simulation geometries have to be considered in comparisons!

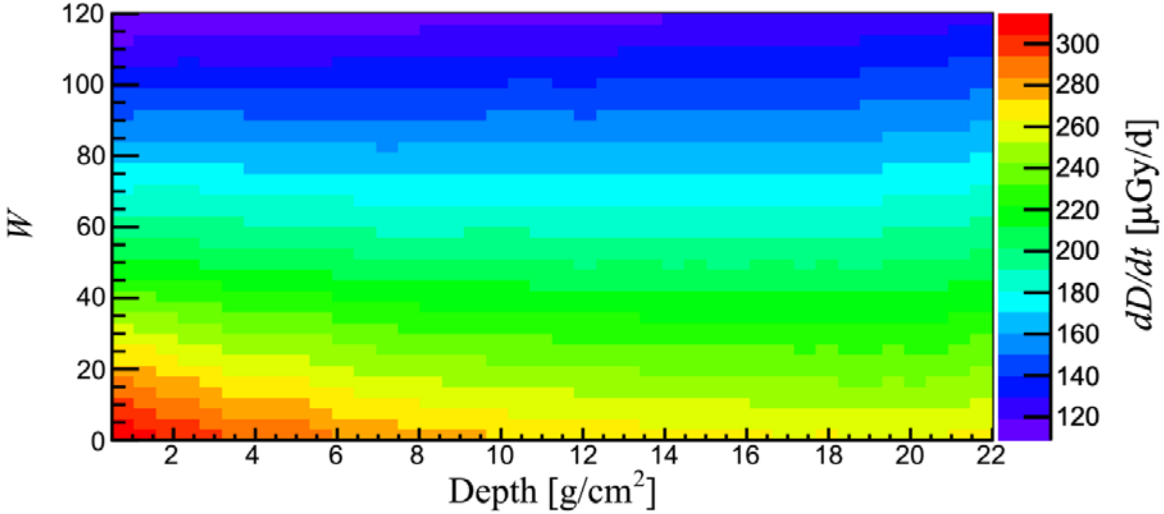
Development of a parameterized radiation model

- Calculate dose rate vs depth for GCR (Z=1-28) for 3 solar modulations (low, medium and high activity)
- Calculate dose rate vs depth for GCR (H, He) for several solar modulation
- Use ratio to scale the result of GCR (H, He)
- Dose rate in Si, dose rate in tissue, dose equivalent rate

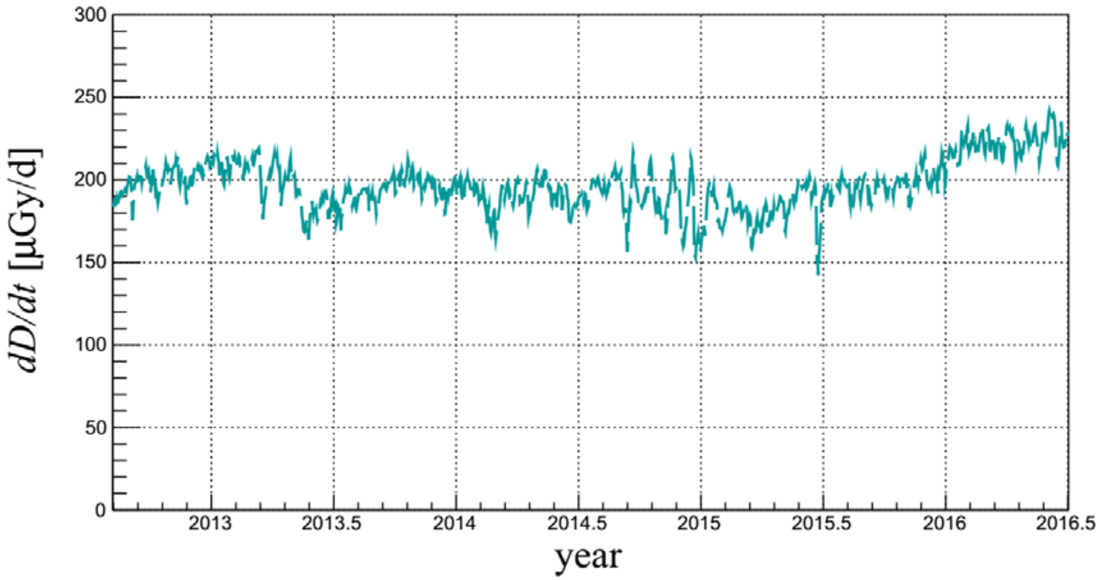
Development of a parameterized radiation model

- decrease of dose rates with depth (low solar activity)
- constant dose rates with depth (higher solar activity)
- surface effect – increase of dose rates





Development of a parameterized radiation model
Dose rate at the Martian surface (22 g/cm^2)



- GCR intensity based on Neutron Monitor data!

Future work: comparison to RAD data
pressure dependence (daily and seasonal variations)
how to derive primary GCR intensity at Mars?

Summary

- Output of DLR and BO-10/BO-14 model similar (<10%); differences in dose rates ≤ 5%

- Publication:
  - Reasonable agreement between different transport models for many particles but severe differences for others
  - Calculated total dose rates are compatible with measurements, but in some cases large discrepancies in the contribution of individual particle types

- Workshop: Orders of magnitude differences in the model results

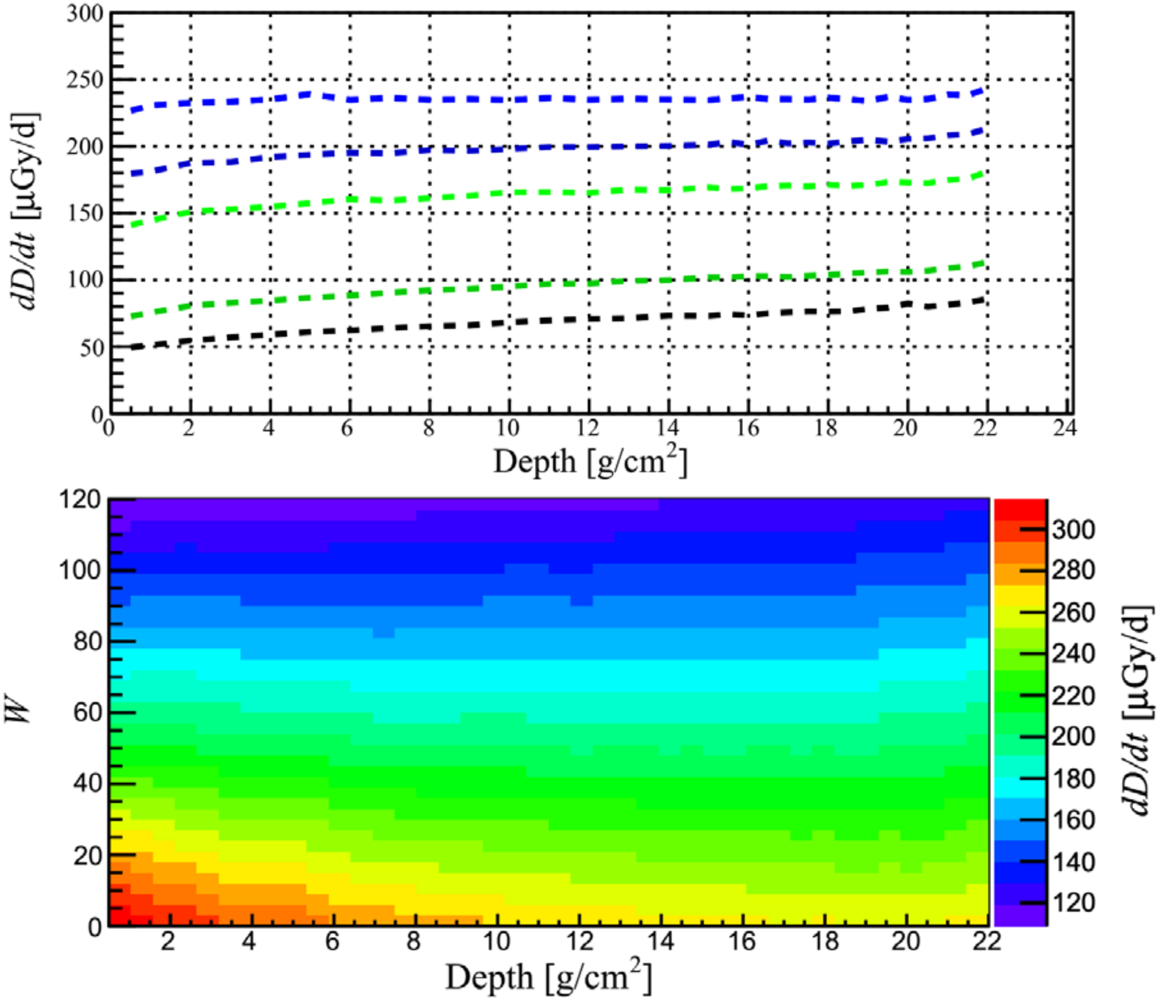
- Promising results from the parameterized model, validation with RAD data needed; determination of primary GCR intensity at Mars is difficult

Overview of calculated dose rates at Martian surface

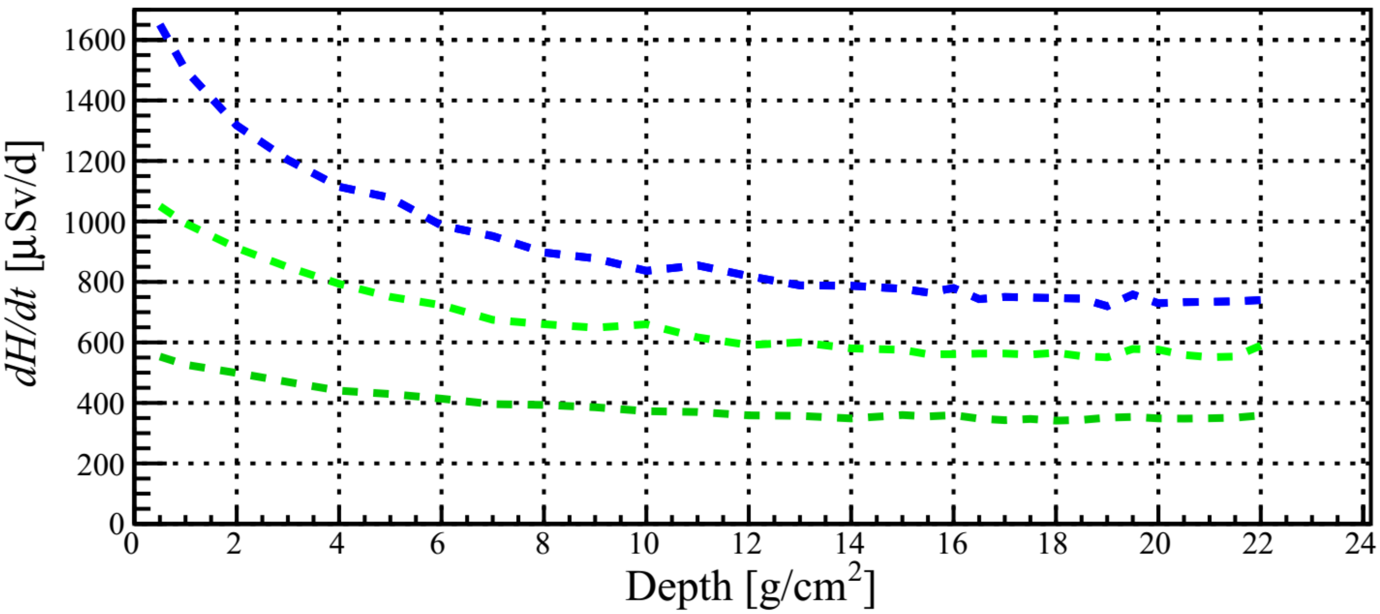
	MSL-RAD	GEANT 4.10.p02					PHITS	OLTARIS	HZETRN
	[Hassler et al., 2014]	[1]	[2] QGSP_BIC, INCL	[3] QGSP_BIC_HP, G4Ion	[4] QGSP_BIC_HP, QMD	[5] QGSP_BERT_HP, G4INCL		2013	/OLTARIS
dose rate in Silicon [mGy/d]		0.16 (0.017)	0.15 (0.17)	0.15 (0.017)	0.15 (0.016)	0.16 (0.017)	0.15 (0.019)	0.13	0.14 (0.019)
dose rate in tissue [mGy/d]	0.21±0.04	0.19 (0.021)	0.19 (0.021)	0.19 (0.020)	0.18 (0.020)	0.20 (0.021)	0.20 (0.024)	0.16	0.18 (0.024)
dose equivalent rate [mSv/d]	0.64±0.12	0.52 (0.063)	0.51 (0.063)	0.51 (0.067)	0.51 (0.069)	0.61 (0.068)	0.60 (0.081)	0.52	0.54 (0.076)
Quality factor	3.05±0.26	2.7 (3.0)	2.7 (3.1)	2.7 (3.3)	2.8 (3.5)	3.0 (3.2)	3.0 (3.4)	3.2	3.0 (3.2)

	MSL-RAD [Hassler et al., 2014]	GEANT 4.10.p02	PHITS	OLTARIS 2013	HZETRN /OLTARIS
GEANT4 physics list setups					
[1]	Physics Lists: emstandard_opt3, G4HadronPhysicsINCLXX, G4IonINCLXX Models: Ions: INCL v5.1.14.2 (0 eV < E < 54 GeV); FTFP (53.9 GeV < E < 1 TeV) Neutrons/Protons: PRECO (0 eV < E < 2 MeV); INCL v5.1.14.2 (1 MeV < E < 3 GeV); Bertini (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[2]	Physics Lists: emstandard_opt3, user defined Models: Ions: INCL v5.1.14.2 (0 eV < E < 48 GeV); FTFP (47.999 GeV < E < 1 TeV) Protons: PRECO (0 eV < E < 2 MeV); INCL v5.1.14.2 (1 MeV < E < 3 GeV); Binary Cascade (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); INCL v5.1.14.2 (19.9 MeV < E < 3 GeV); Binary Cascade (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[3]	Lists: emstandard_opt3, G4HadronPhysicsQGSP_BIC_HP, G4IonPhysics Models: Ions: Binary Light Ion Cascade (0 eV < E < 4 GeV); FTFP (2 GeV < E < 100 TeV) Protons: Binary Cascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); Binary Cascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[4]	Physics Lists: emstandard_opt3, G4HadronPhysicsQGSP_BIC_HP, G4IonQMDPhysics Models: Ions: QMDModel (0 eV < E < 10 TeV) Protons: Binary Cascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); Binary Cascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[5]	Physics Lists: emstandard_opt3, G4HadronPhysicsQGSP_BERT_HP, G4IonINCLXX Models: Ions: INCL v5.1.14.2 (0 eV < E < 54 GeV); FTFP (53.9 GeV < E < 1 TeV) Protons: BertiniCascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); BertiniCascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				

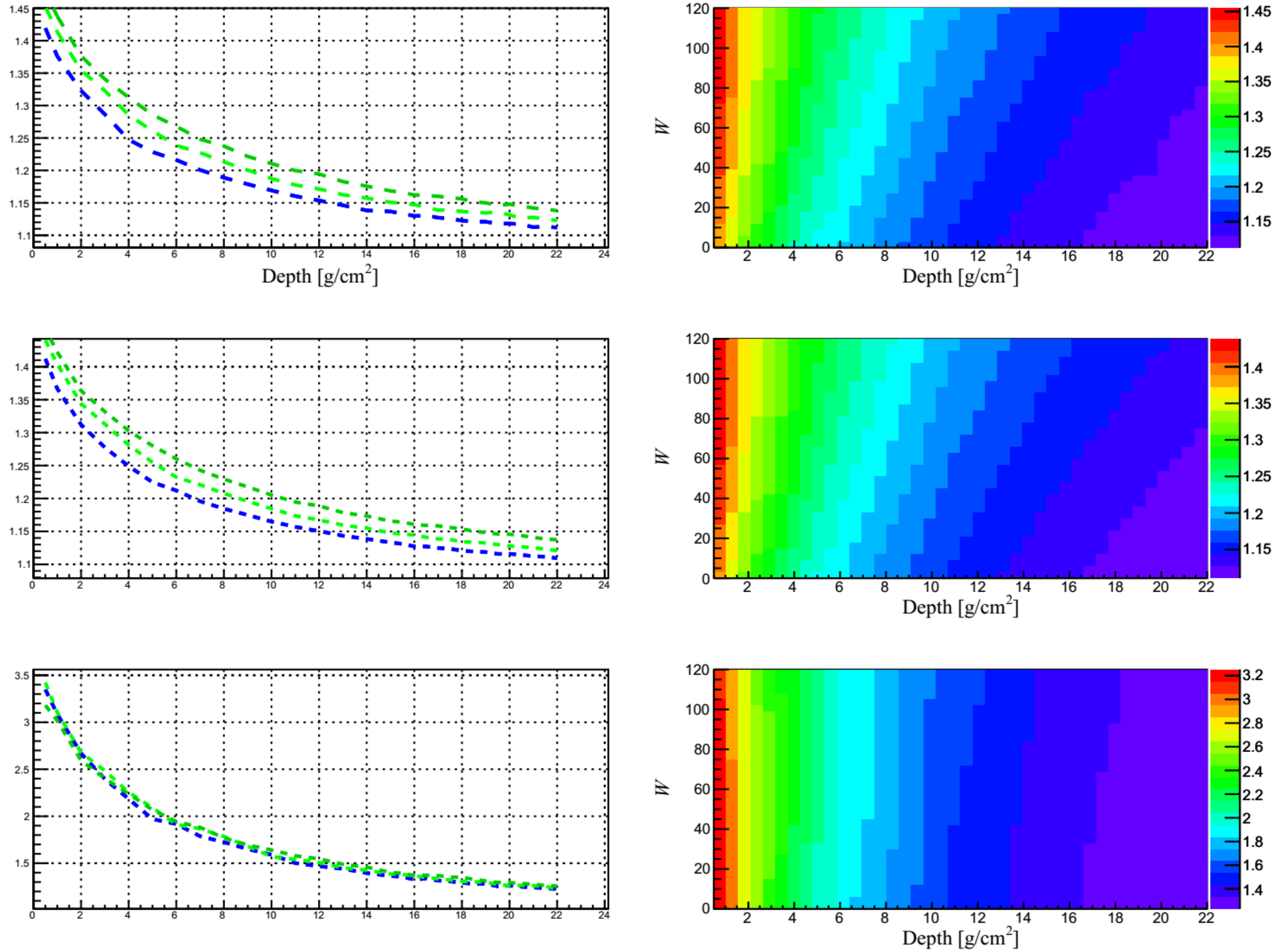
Development of a parameterized radiation model

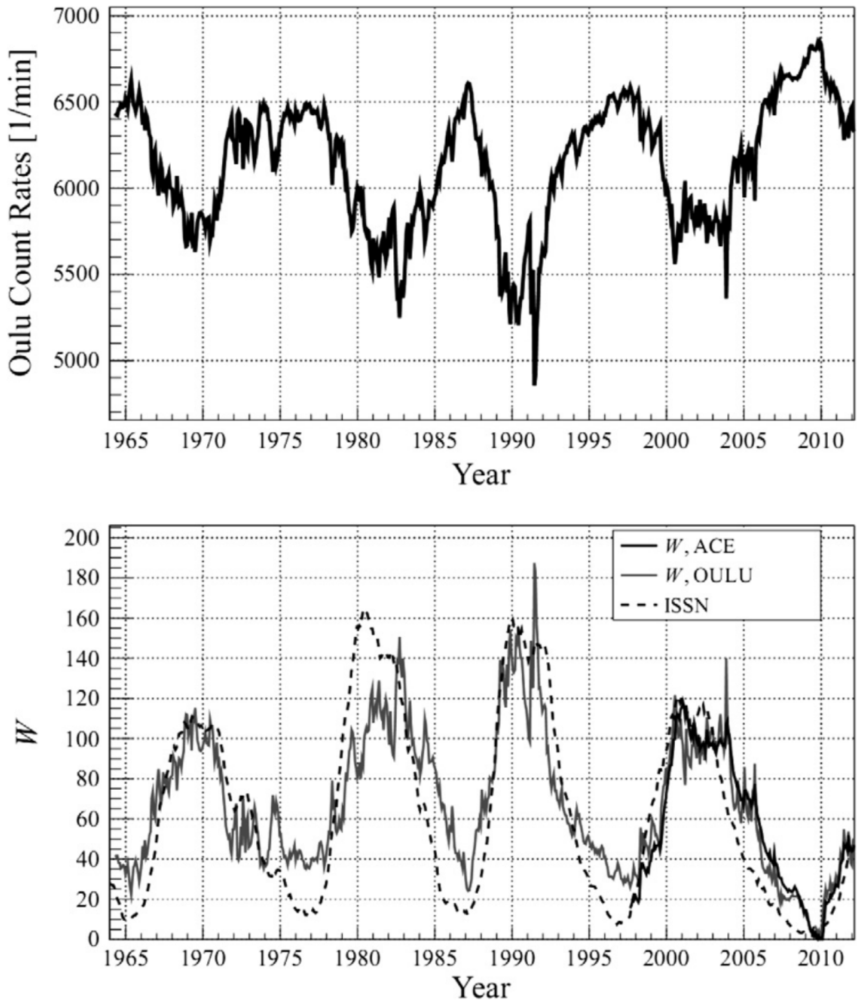


Development of a parameterized radiation model



Development of a parameterized radiation model




7000
6500
6000
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5000
Oulu Count Rates [1/min]
1965
1970
1975
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1985
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1995
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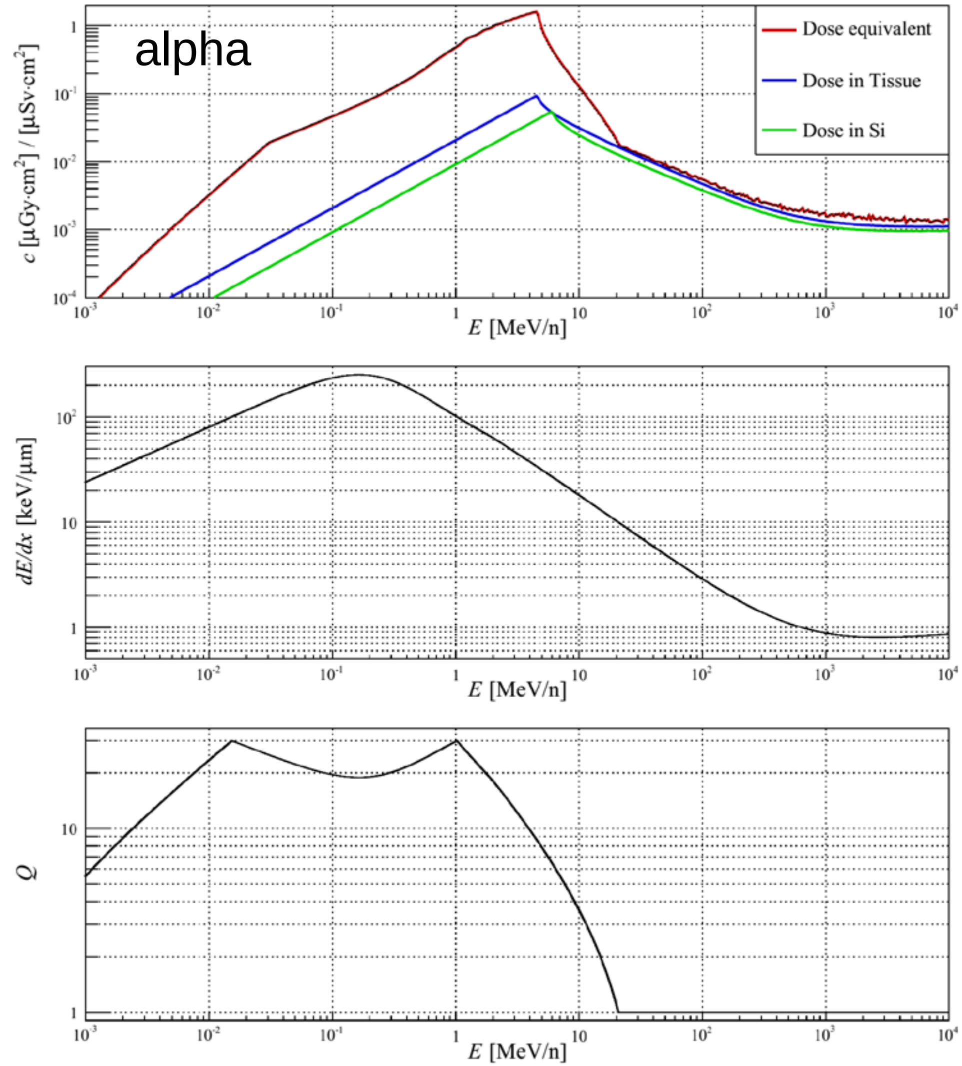
2005
2010
Year
200
180
160
140
120
100
80
60
40
20
0
W
W, ACE
W, OULU
ISSN
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

Fluence to dose conversion

- Pre-calculated fluence-to-dose-conversion factors *c*
- 0.5 mm slab of
  - Tissue
  - Water
  - Si
- $\dot{D} = \int dE \cdot c_D \cdot f$
- $\dot{H} = \int dE \cdot c_H \cdot f$



Electron, muon, pion

- No experimental data
- $e^{-/+}$: G4/PHITS agree, HZETRN lower
- $\mu^{-/+}$: differences below 100 MeV
- $\pi^{-/+}$: differences of several orders of magnitude