Radiation transport calculations for cosmic radiation

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Akira Endo and Tatsuhiko Sato*
ICRP Committee 2 & Task Group 4 (DOCAL)
* Task Group 67 (Radiation Protection in Space)

Introduction

The presentation reviews Chapters 5 & 6 of the draft by TG67

"Assessment of Radiation Exposure of Astronauts in Space"

- Chapter 5: Radiation fields inside spacecrafts and on planetary surfaces
- Chapter 6: Radiation field and doses in human body

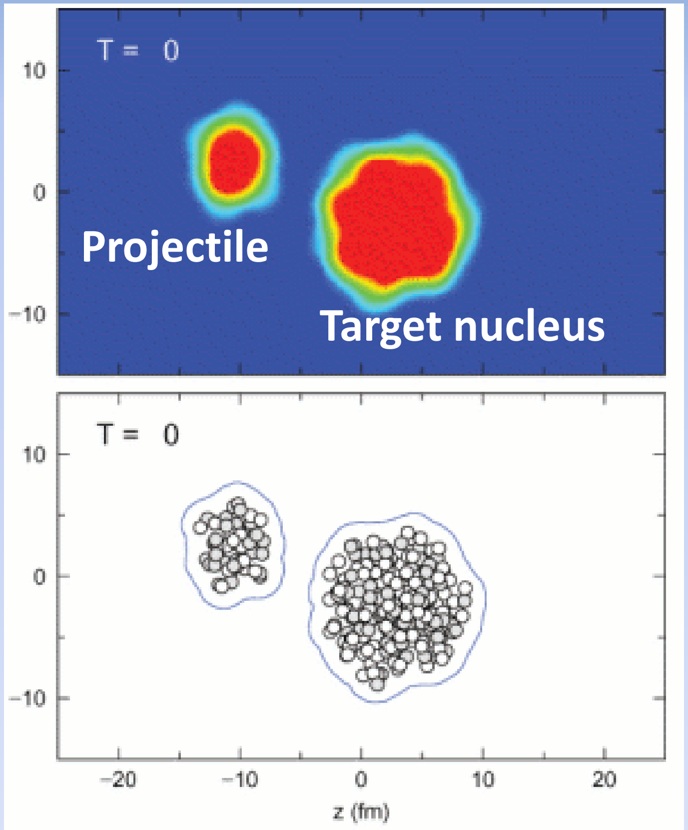
Main points of the presentation :

- Physics and computer codes for cosmic radiation transport
- Application to space radiation protection
  - Assessment of radiation environment in spacecrafts and performance of shielding materials
  - Analysis of organ doses using the ICRP reference phantoms, and a phantom/spacecraft model

Overview of interactions of cosmic radiation

Primary radiation in space

- proton, electron, HZE nuclei



Secondary radiation in spacecraft and human body

- Nucleon (proton, neutron)
  Evaporation, knockout
- Light particles (d, t, h, α)
  Evaporation, knockout, pickup
- Heavy ions
  Projectile & Target fragments
- Pion, Kaon, Anti-nucleon
  Projectile energy > 500 MeV/u

Various particles of wide energy → Various LETs

Computer codes for cosmic radiation transport

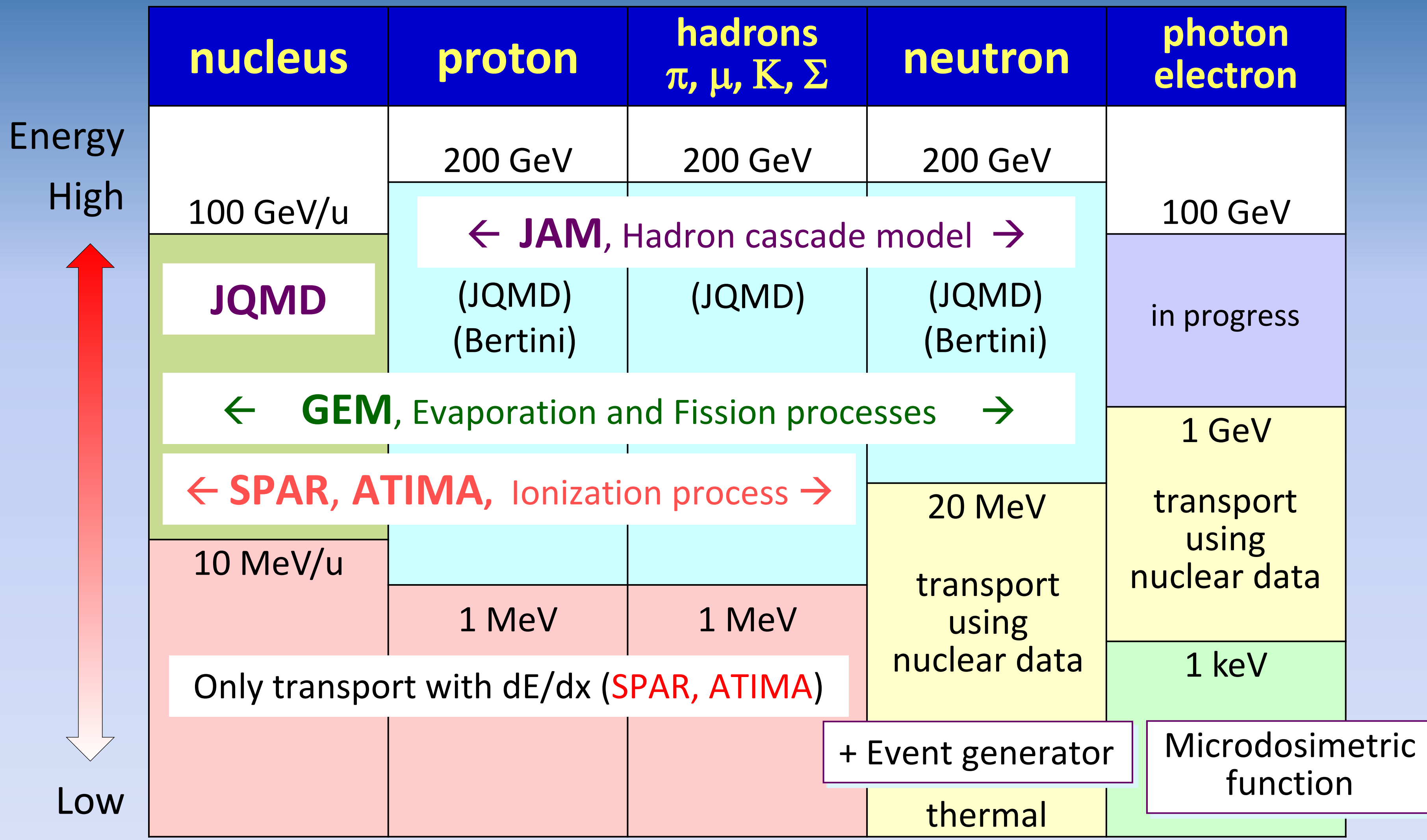
- **HZETRN** (NASA)
  - 1-D deterministic code
  - Used for space radiation protection

- **FLUKA** (CERN, INFN)
- **GEANT4** (Worldwide collabo.)
- **HETC-HEDS** (ORNL)
- **MCNPX** (LANL)
- **PHITS** (JAEA, RIST, others)
- **SHIELD-HIT** (INR)

- 3-D Monte Carlo codes
- Various applications
  - Reactor and accelerator physics & engineering
  - Detector design
  - Radiotherapy & dosimetry
  - Radiobiology
  - **Space application**

Physics models used in PHITS

PHITS: **P**article and **H**eavy **I**on **T**ransport code **S**ystem



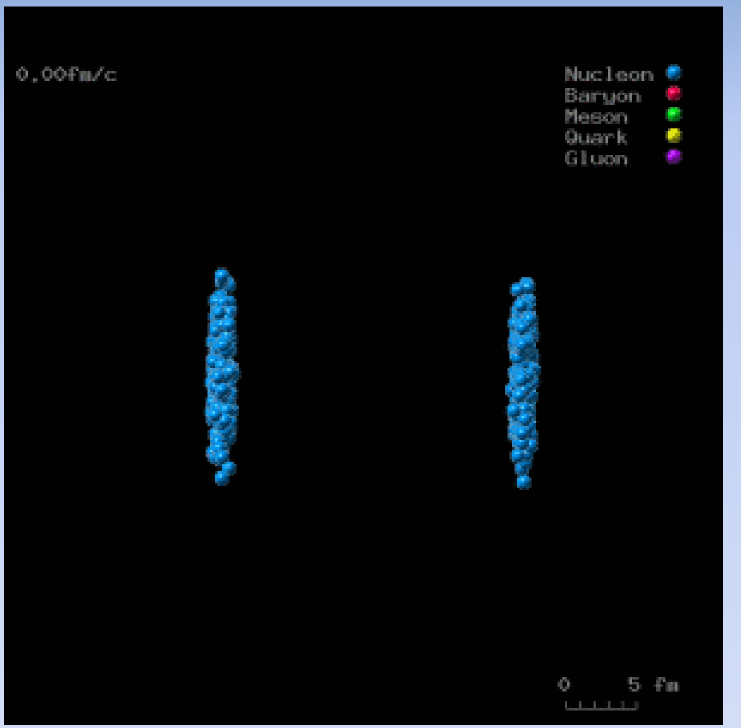
JQMD: JAERI Quantum Molecular Dynamics model

JAM: Jet AA Microscopic transport model

JAM (Jet AA Microscopic) transport model

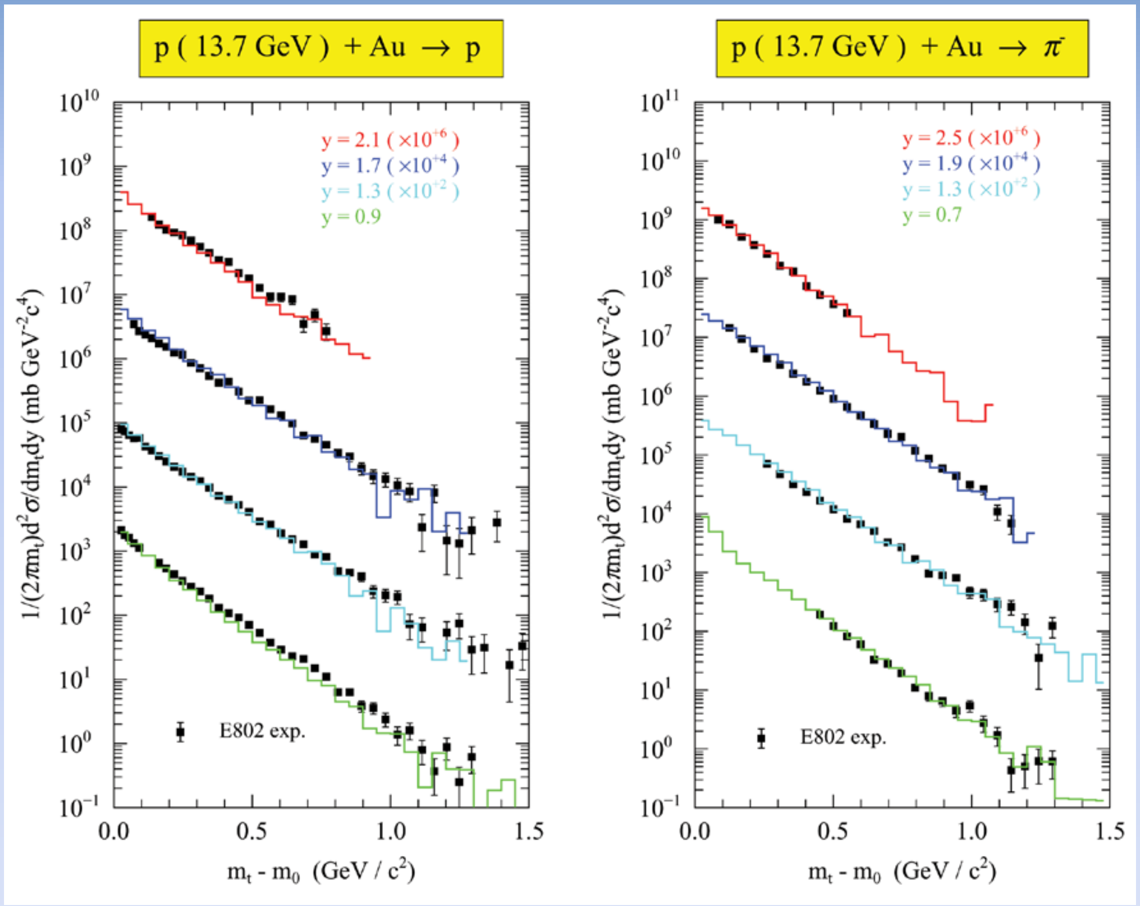
JAM is a hadronic cascade model, which treats all established hadronic states, including resonances with explicit spin and isospin, as well as their anti-particles.

Au + Au 200GeV/u



119 kinds of Mesons

170 kinds of Baryons

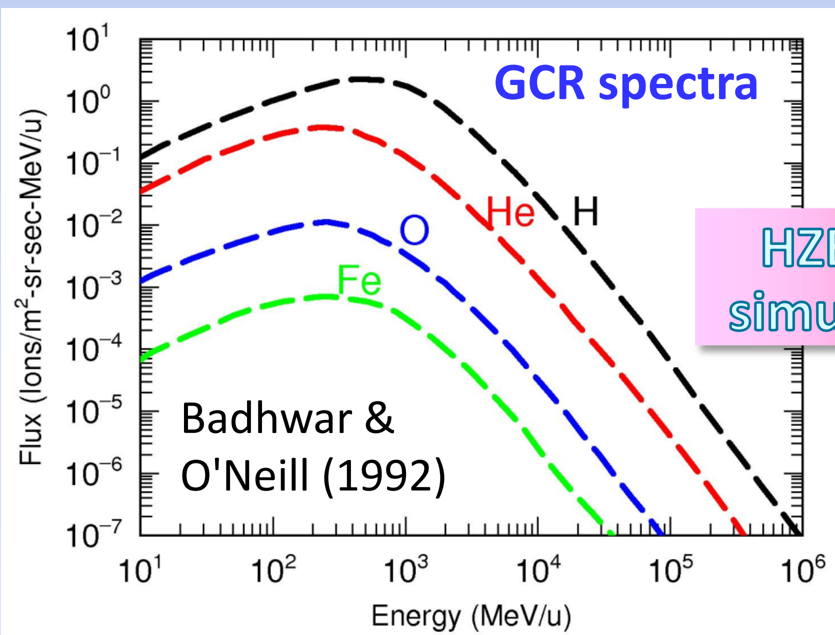


Nara (2000)

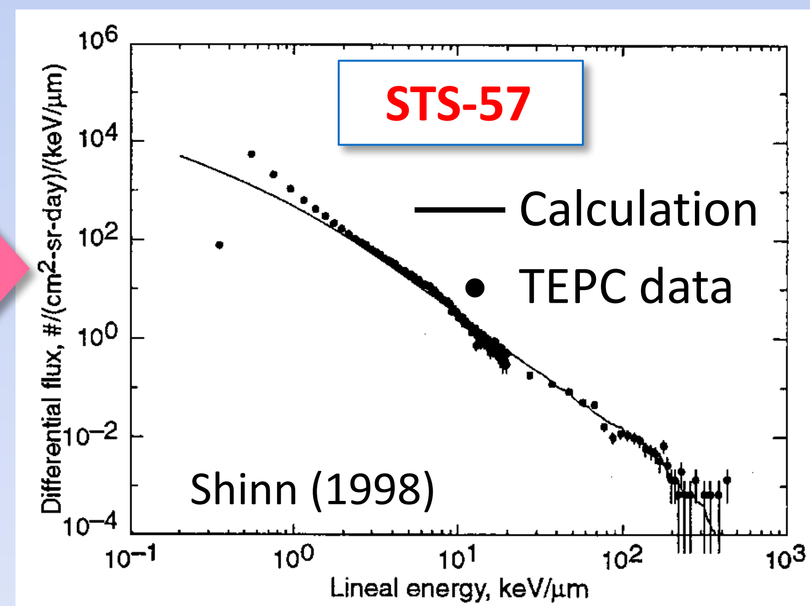
Radiation environment simulation and validation

NCRP153 (2006)

Mission	Date	Altitude (km)	Shielding	Dose equivalent rate (mSv/d)	
				Measurement	Calculation
STS-57	1993	298	Payload bay	0.442	**0.434**
Mir-18	1995	390		0.461	**0.526**
STS-81	1997	400	Poly 12 inches	0.290	**0.297**
STS-89	1998	393	Al 3 inches	0.445	**0.488**



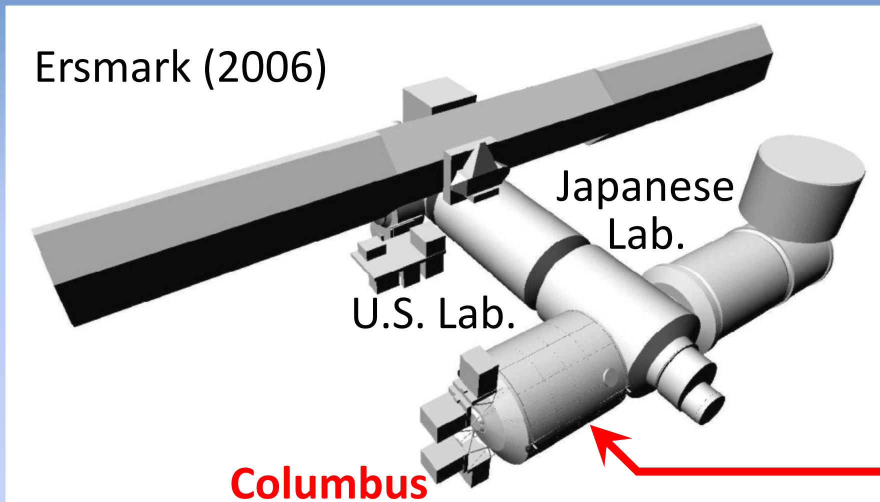
HZETRN simulation

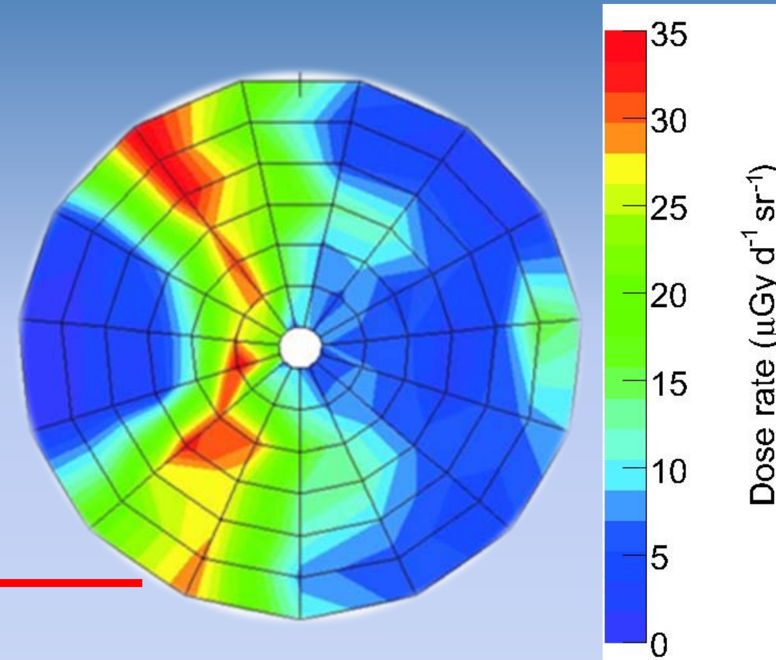


. PROTECTION

Radiation environment simulation by 3-dimentional Monte Carlo code

Columbus & ISS models in GEANT4

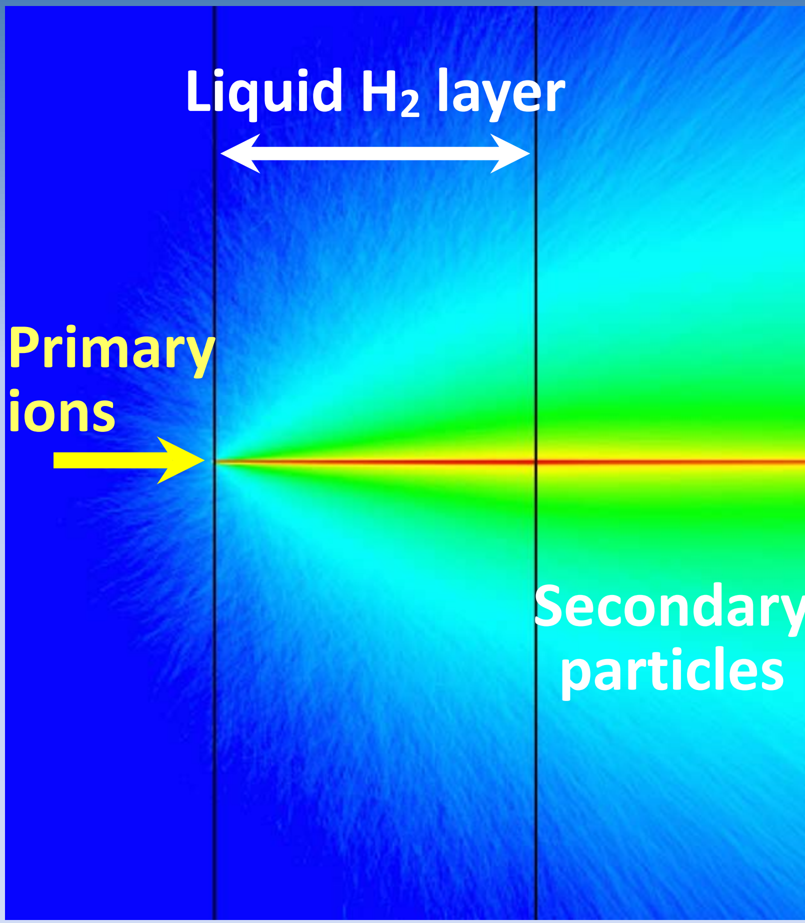




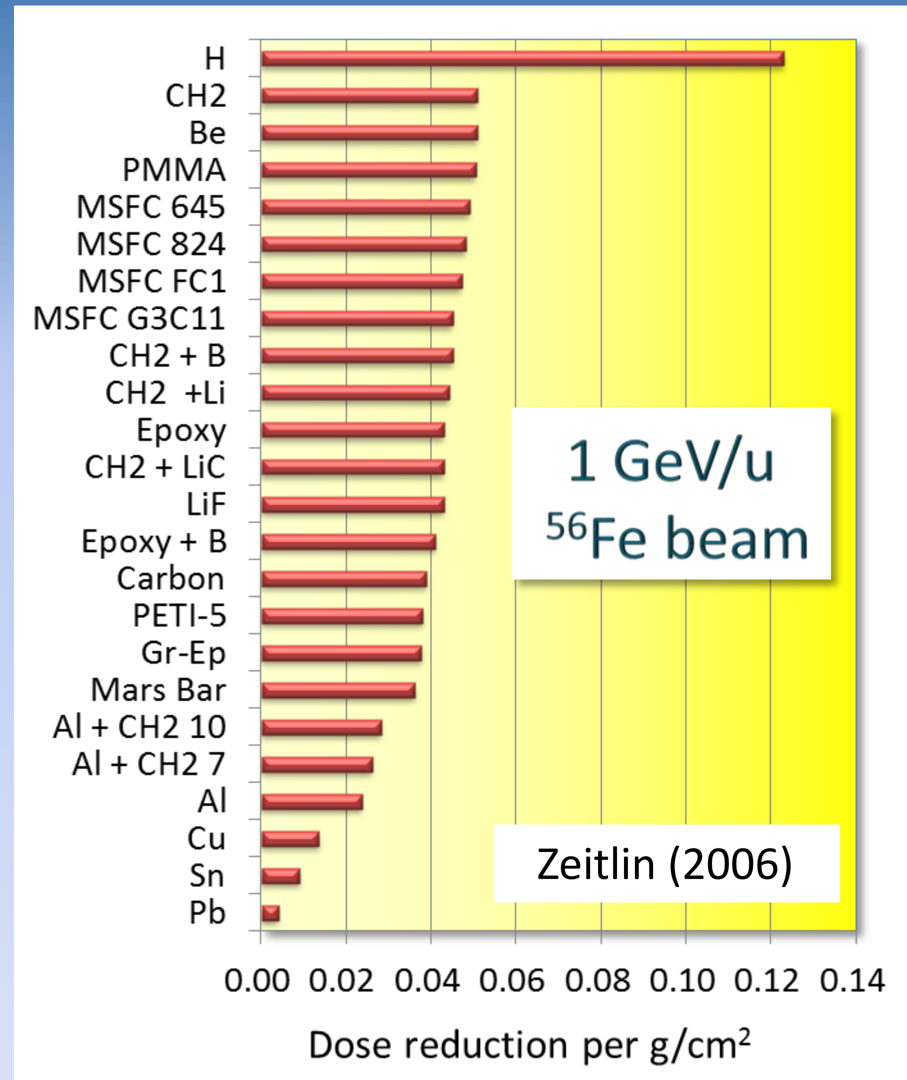
Geometry configuration	CPU-days*
Columbus without ISS geometry	68
Columbus with ISS geometry (shown in the above left figure)	**190 (for proton)** **20 (for neutron)**

* Using AMD Athlon 2000+ processors

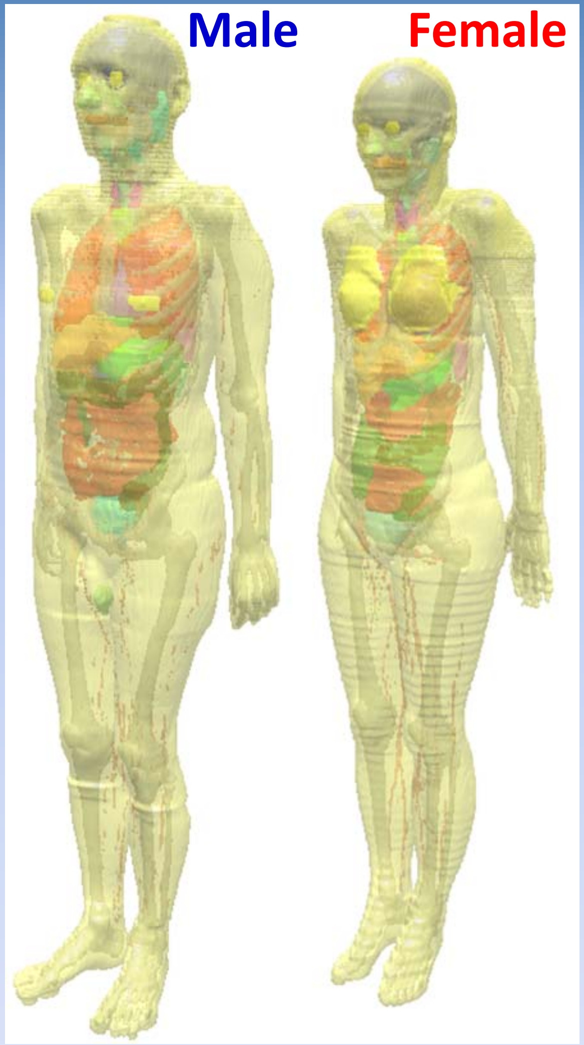
Assessment of shielding performance



Radiation transport calculation provides advantages to shielding design for cosmic radiation



Dose calculation



ICRP/ICRU adult male and female reference computational phantoms (ICRP110)

- 3-dimensional representation of human anatomy
  - Constructed from CT data of real persons
  - Reference anatomical values of ICRP89

Coupled to the PHITS code

- Analysis of radiation field in the body
- Calculation of dose conversion coefficients and quality factors

Protection quantities in space: Mean absorbed dose & Dose equivalent

Mean absorbed dose:

$$D_{T,R} = \int_E d_{T,R}(E) \frac{d\Phi_R}{dE} dE$$

$d_{T,R}(E)$: fluence-to-absorbed dose conversion coefficients for the organ *T*

$d\Phi_R/dE$: spectral fluence of particles of type R incident on the body

Radiation environment in space consists of various components of various LETs ⇨ ***Q(L) is better than w_R***

Equivalent dose:

$$H_T = \sum_R w_R D_{T,R}$$

w_R = 20 for heavy ions in ICRP103

Dose equivalent:

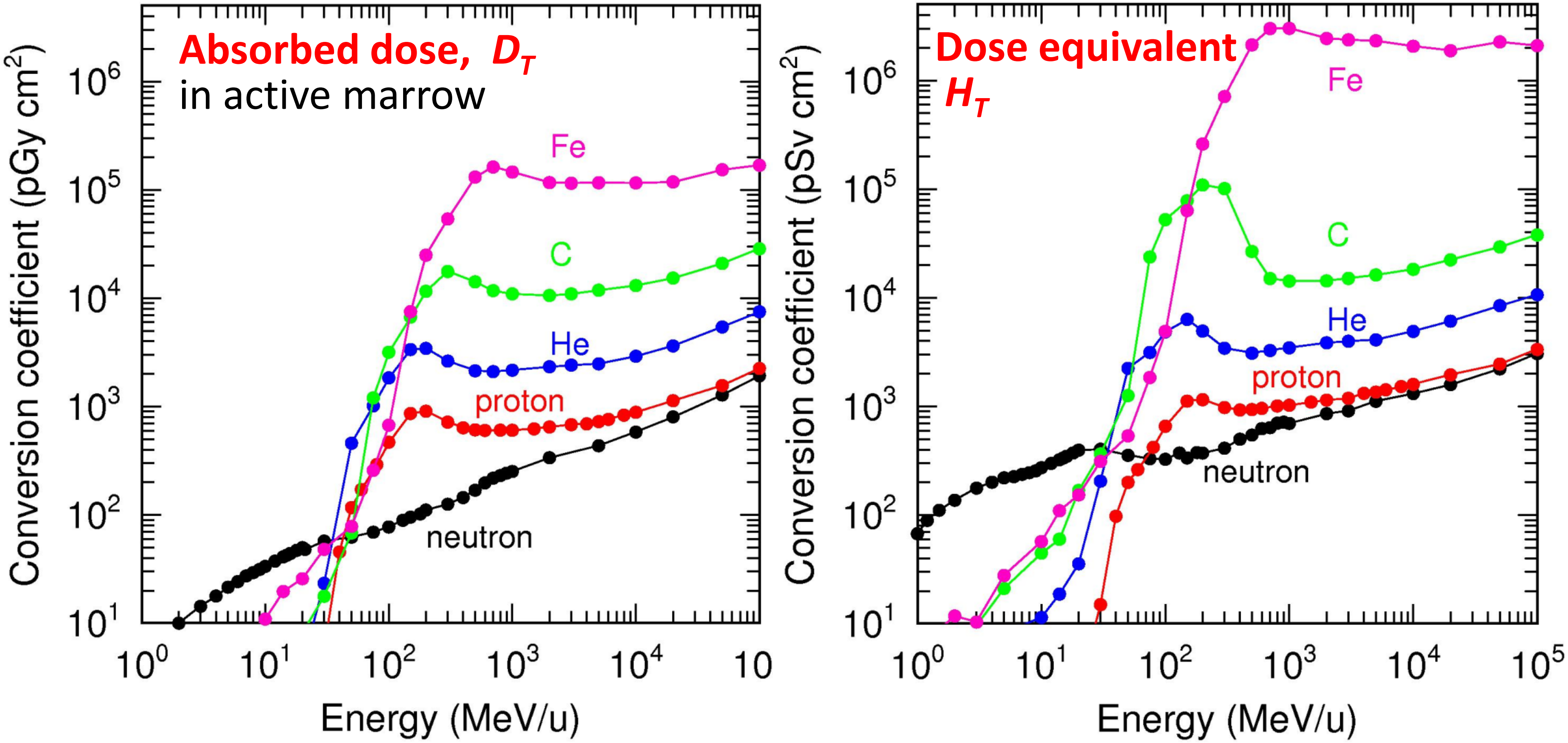
$$H_T = \sum_R Q_{T,R} D_{T,R}$$

$Q_{T,R}$: quality factor based on Q(L)

Space organizations (e.g. NASA, ESA) have been adopting this approach

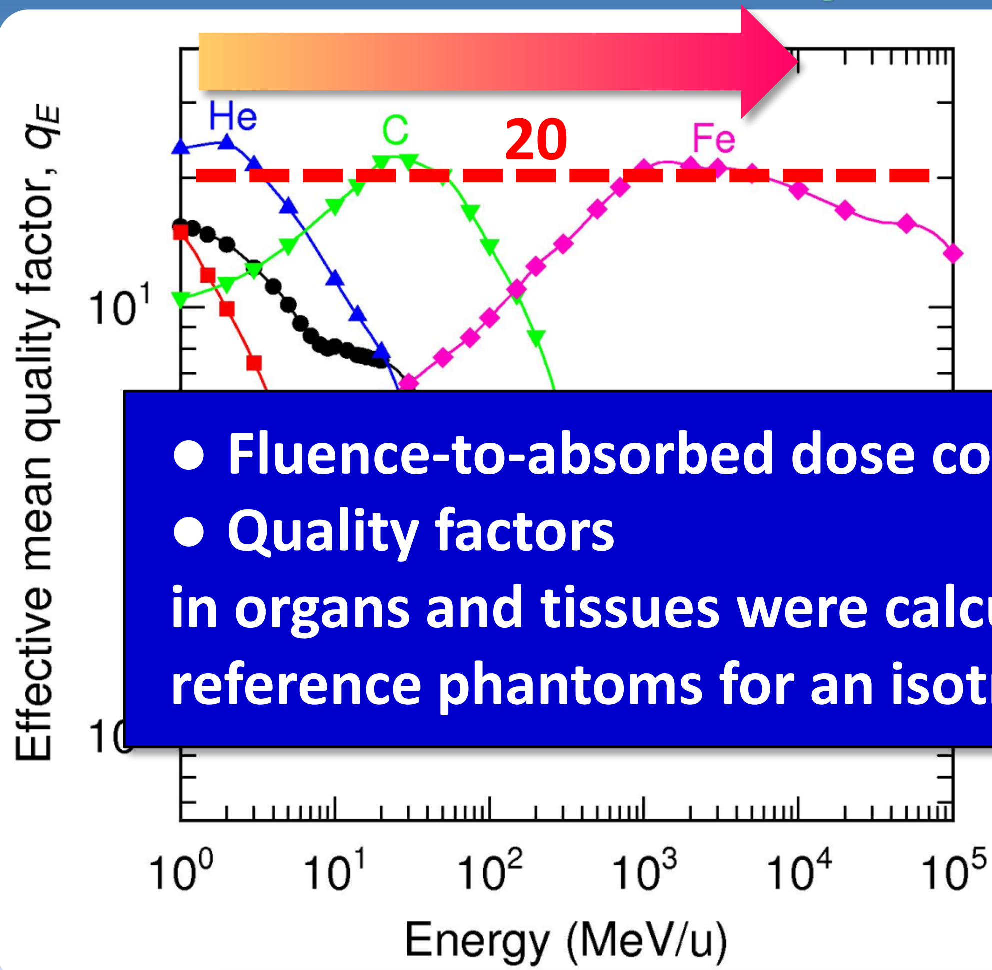
Absorbed dose and Dose equivalent

Sato (2010)

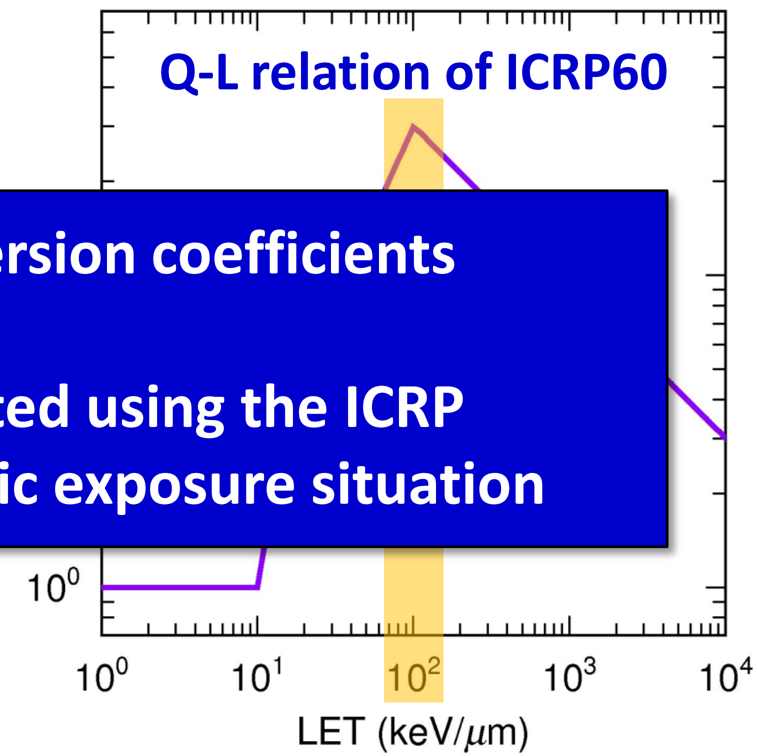


- ***D_T* and *H_T* increase with the atomic number of incident particle**
- **Shapes of energy-dependence curves are different between *D_T* and *H_T***

Mean quality factor



$$q_E = \sum_T w_T Q_T D_T / \sum_T w_T D_T$$



- **Fluence-to-absorbed dose conversion coefficients**
- **Quality factors**

in organs and tissues were calculated using the ICRP reference phantoms for an isotropic exposure situation

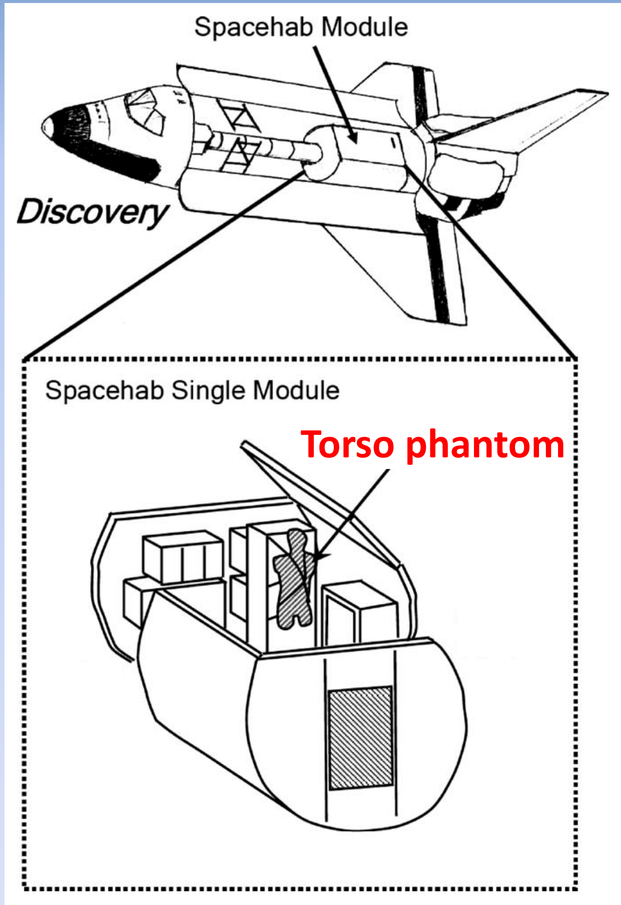
q_E has a peak structure

- **Peak values (~ 20) are independent of the atomic number**
- **Peak energies increase with the atomic number**

Dose calculation using a phantom/spacecraft model

Measurement in the STS-91

Yasuda (2000)



Cucinotta (2008)

Organ/ Tissue	Dose equivalent (mSv)	
	Measurement	HZETRN/QMSFRG
Skin	4.5 ± 0.05	**4.7**
Thyroid	4.0 ± 0.21	**4.0**
Bone surface	5.2 ± 0.22	**4.0**
Esophagus	3.4 ± 0.49	**3.7**
Lung	4.4 ± 0.76	**3.8**
Stomach	4.3 ± 0.94	**3.6**
Liver	4.0 ± 0.51	**3.7**
Bone marrow	3.4 ± 0.40	**3.9**
Colon	3.6 ± 0.42	**3.9**
Bladder	3.6 ± 0.24	**3.5**
Gonad	4.7 ± 0.71	**3.9**
Chest	4.5 ± 0.11	**4.5**

Concluding remarks

Radiation transport technique is an essential tool for space radiation protection

- Assessment of radiation environment
- Shielding design & calculation
- Dose assessment and instrument development
  - Absorbed dose conversion coefficients and quality factors in organs calculated using the ICRP phantoms are presented in the Annex

Outlook

- Validation and improvement of computer codes and models
  - Comparison with experiment, intercomparison between codes
- Development of methods to estimate biological effect
  - Combination of macroscopic radiation transport method and microdosimetric model, e.g., track structure-based model

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Thank you for your attention

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