

Radiation Shielding Simulation For Interplanetary Manned Missions

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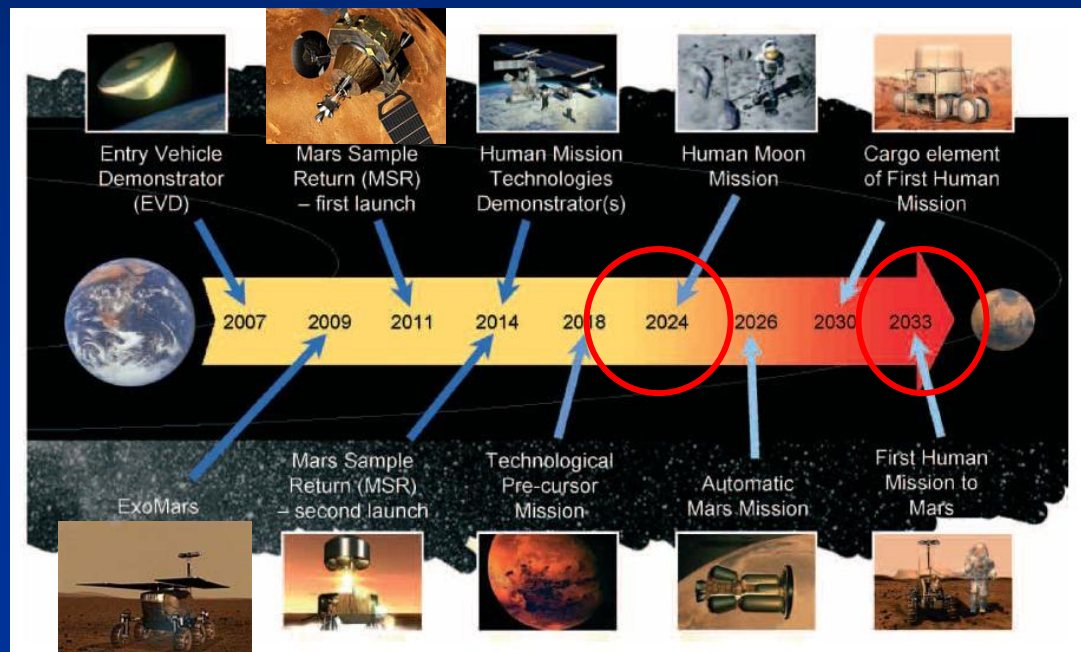
Susanna Guatelli

Geant 4



Context

- Planetary exploration has grown into a major player in the vision of space science organizations like ESA and NASA
- AURORA**: European long term plan for the **robotic** and **human** exploration of the solar system
 - with Mars, the Moon and the asteroids as the most likely targets

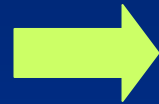


Human missions to Mars

The effects of space radiation on astronauts are an important concern

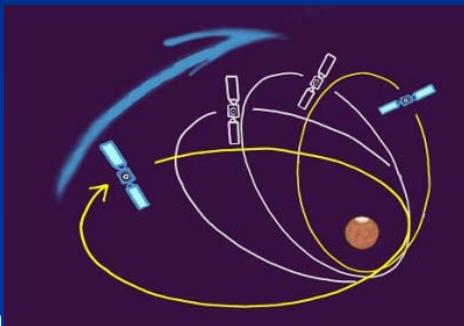


The crew is exposed to the space radiation environment



- Radiation sickness
- Damage to the central nervous system
- Cancer

Optimize trajectories



Susan

Shielding



This project

In the framework of the AURORA programme of ESA

Scope

Quantitative evaluation of the physical effects of space radiation in interplanetary manned missions

Transfer vehicles



On planetary surface



First **quantitative** evaluation of the shielding properties of **conceptual designs**
Comparison among different shielding options



Guidelines for future **mission design** and concrete **engineering studies**

Strategy

Risk assessment

- Reliable model to evaluate **acceptable risk** (*risk is not measured, it is **predicted** by a model*)

Sound physics results

- Distinguish **physical** and **biological** effects
- **Validation** of the physics modelling components
- Control **systematics**
- Quantitative **mathematical analysis** of results

Advanced technology

- **Object Oriented** technology
- Rigorous **software process**
- Software **tools** based on modern technology

Transparency

- **Open source** software tools
- Publicly distributed software

All the features above are relevant to a **mission-critical long-range** space science project

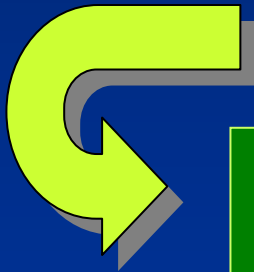
Uncertainties and systematics

Large uncertainties

- Radiation environment
- Mission trajectories and duration
- Characteristics of spacecrafts
- Biological effects of radiation exposure

Modelling hadronic interactions

- Intrinsic complexity of the underlying theory
- Scarce and imprecise experimental data
- Monte Carlo codes still evolving in this domain



Focus on **physics** in the 1st study cycle

Biological effects on top of sound physics in a following cycle

Relative comparison of shielding configurations

Instead of absolute dose calculations

Multiple hadronic models to evaluate **systematics**

Software Strategy

Software Development Process

- Iterative and incremental model
- Based on the Unified Process
- Specifically tailored to the project
- Mapped onto ISO 15504

Object Oriented Technology

- Openness to extensions and evolution
- Maintainability over a long time scale

Monte Carlo simulation

- Model radiation environment
- Model shielding configuration
 - Track particles in matter



Geant 4

Functionality
(geometry, physics, interactivity)

OO technology

Rigorous **validation**

Physical Analysis

Evaluate energy
deposited in the astronaut



AIDA

Abstract Interfaces for
Data Analysis

Independence from any
specific analysis tools

Statistical Analysis

Compare shielding options
quantitatively

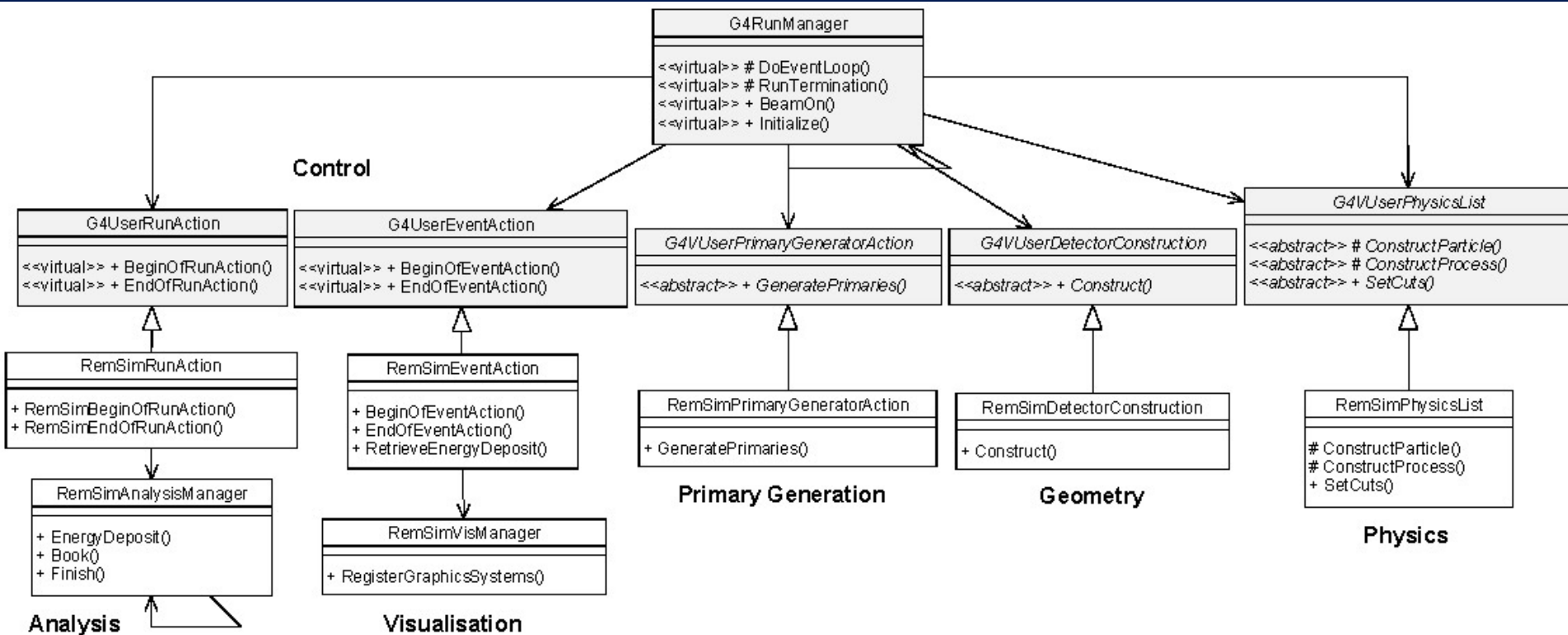


**Statistical
Toolkit**

Richest collection of
goodness-of-fit tests
for data comparison

AIDA compliant

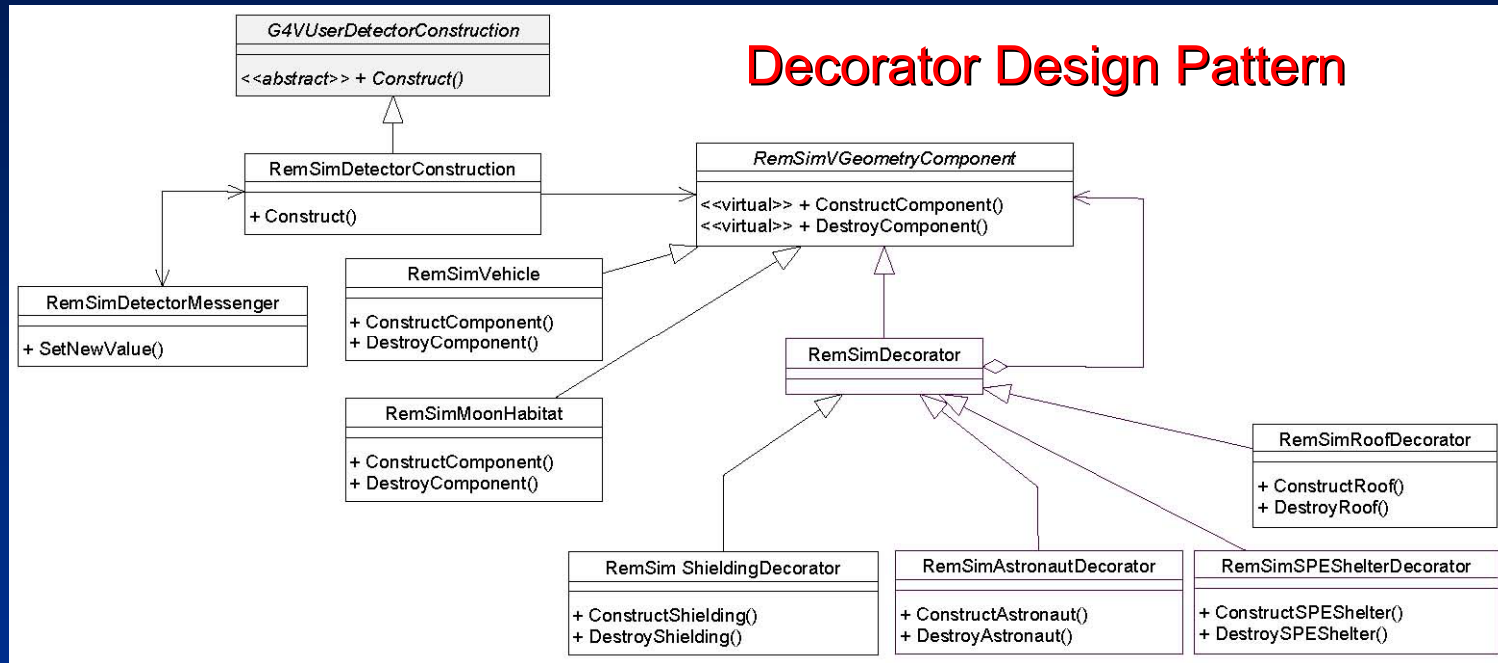
Architecture of the Geant4 application



Component-based architecture

- Each component has a specific responsibility
- Flexibility, extensibility and maintainability

Geometry and materials



Dynamically configure the simulation with

- Habitat type
- Shielding geometry
- Material
- Astronaut's location

Primary particle generation

Conservative assumptions for risk assessment

CREME96

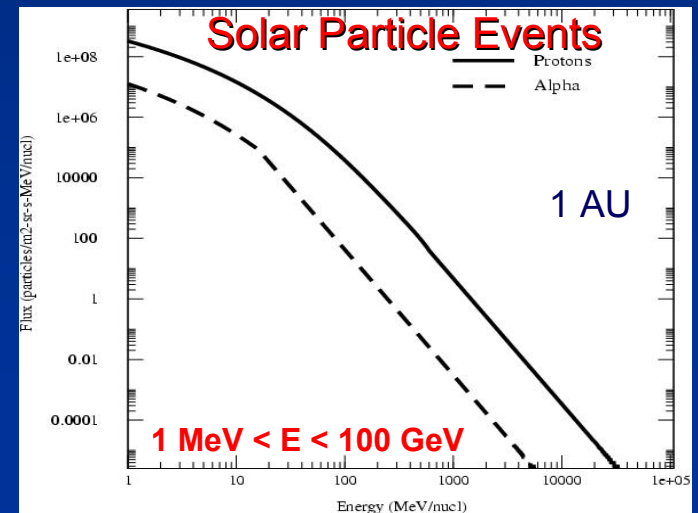
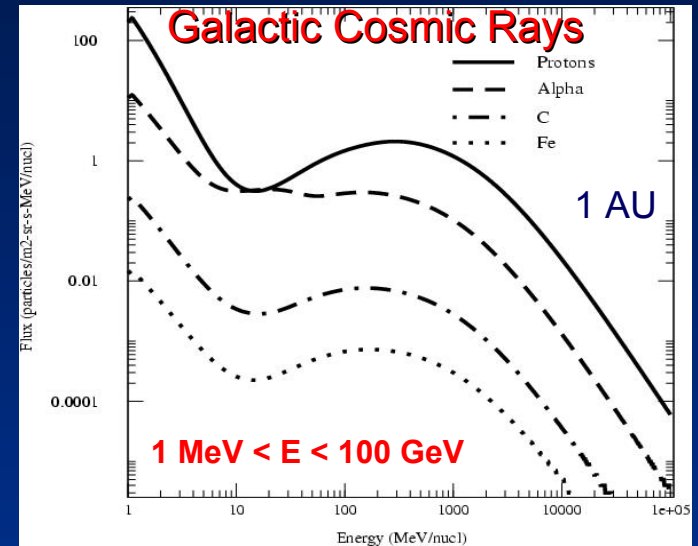
Radiation environment models
ECSS standard

Galactic Cosmic Rays

- 1977 solar minimum
- Anti-correlation with solar activity

Solar Particle Events

- October 1989 event
- 99% worst case



Electromagnetic physics

- Geant4 **Low Energy Package** for:
 - p, α , ions (model based on ICRU49 parameterisation)
 - photons and electrons (model based on the Livermore Libraries)
- Geant4 **Standard Package** for positrons and muons
- Low Energy Electromagnetic Package → overall better accuracy
 - Demonstrated by validation studies

Hadronic Physics

- Elastic and inelastic hadronic scattering
- Alternative models of the inelastic scattering of protons, neutrons, pions:

Hadronic inelastic process	Binary set	Bertini set
Low energy range <i>(cascade + preequilibrium + nuclear deexcitation)</i>	Binary Cascade + Precompound + Deexcitation <i>(up to 10. GeV)</i>	Bertini Cascade <i>(up to 3.2 GeV)</i>
Intermediate energy range <i>(up to E = 25 GeV)</i>	Low Energy Parameterised	
High energy range <i>(20. GeV < E < 100. GeV)</i>	Quark Gluon String Model	

- α inelastic scattering
 - Low Energy Parameterized model up to E = 100 MeV
 - Binary Ion model

Shielding studies



Inflatable Habitat

- Shielding materials
- Shielding thickness
- Comparison to rigid habitats



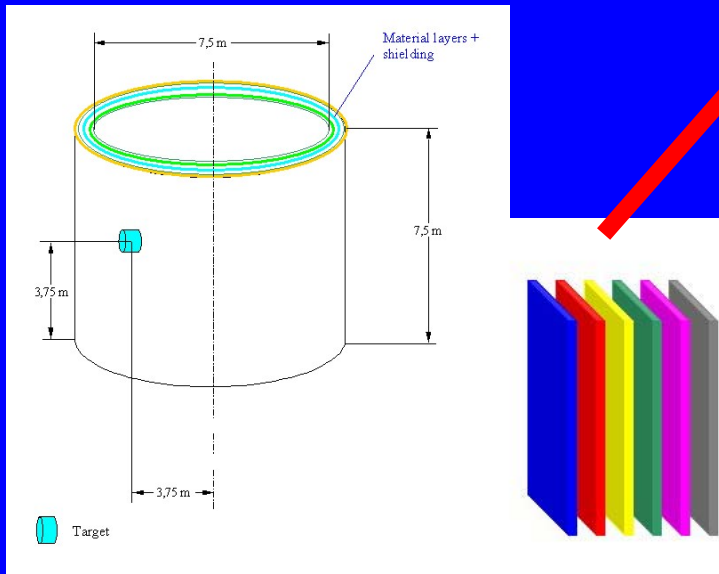
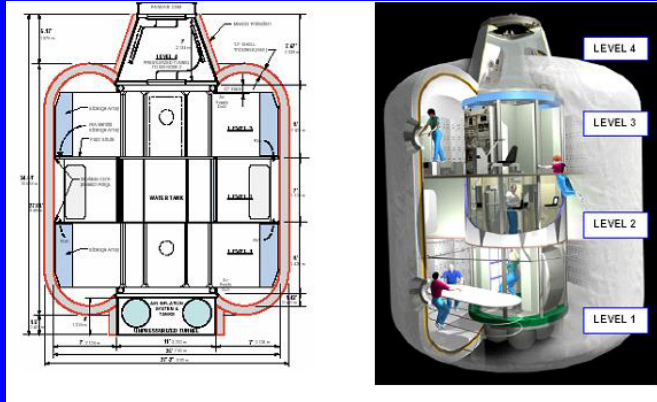
Planet surface habitats

- Shielding with lunar regolith
- Comparison to a rigid habitat

Inflatable habitat

Multilayer structure

- External thermal protection blanket
 - *Betacloth and mylar*
- Meteoroid and debris protection
 - *Nextel (bullet proof material) and open cell foam*
- Structural layer
 - *Kevlar*
- Redundant bladder
 - *Polyethylene, polyacrylate, EVOH, kevlar, nomex*

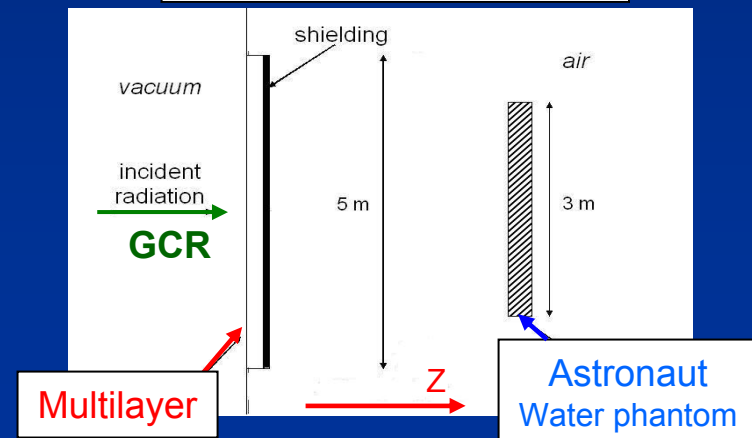


Engineering model by ALENIA SPAZIO

Simplified geometry
Retains the essential characteristics for a
shielding characterization

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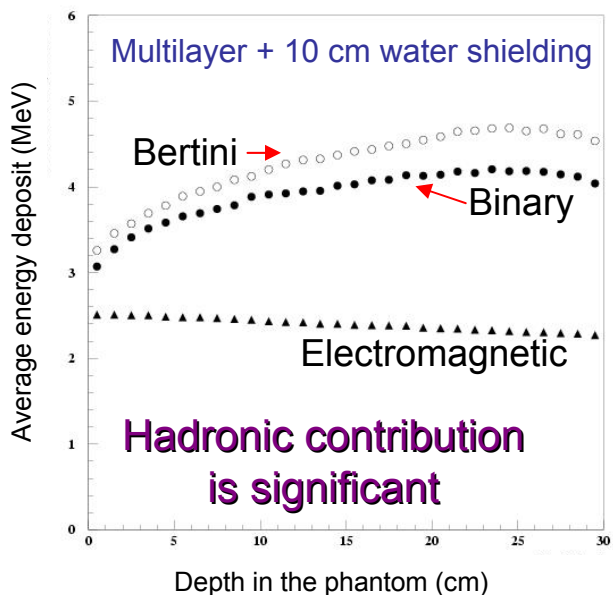
Experimental set-up



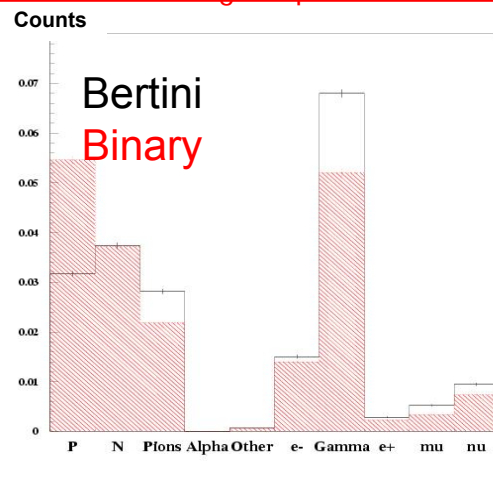
Systematics of hadronic modelling

Study of possible **systematic effects** related to hadronic physics modelling
 Comparison of the energy deposit in the phantom with different hadronic models

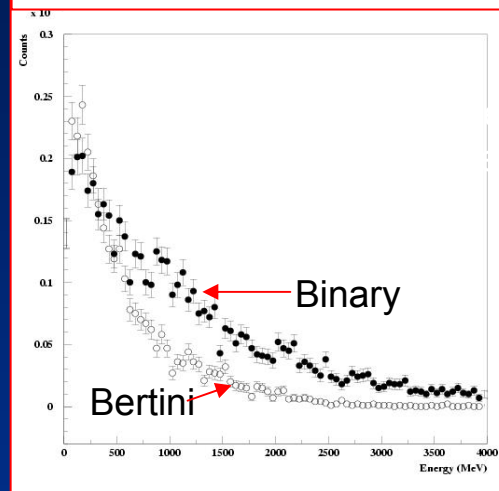
Energy deposit profile of GCR proton



Average no. of secondary particles reaching the phantom



Energy of secondary p



Different energy deposit profiles and secondary product patterns
Kolmogorov Smirnov Test: p-value < 0.05

Physics models	Energy deposit in the phantom
Electromagnetic	71.9 ± 0.2 MeV
Hadronic-Bertini	128.0 ± 0.4 MeV
Hadronic-Binary	117.3 ± 0.4

~10 % difference compatible with experimental validation of Geant4 hadronic models

Shielding thickness

Impossible to shield galactic cosmic rays completely!

The shielding modulates the fraction of GCR reaching the phantom

Secondary particles are also generated in the shielding material

Effect of **5 cm** and **10 cm** water shielding + inflatable multi-layer

% GCR p reaching the phantom

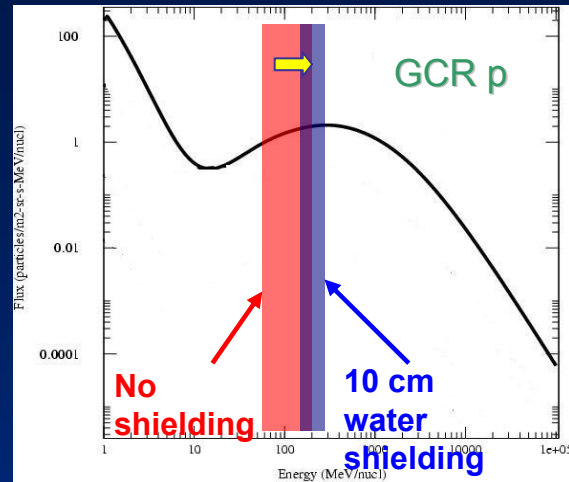
	5 cm water	10 cm water
EM + Bertini	88.7 ± 0.2	83.3 ± 0.2
EM + Binary	88.0 ± 0.2	82.3 ± 0.2

Energy deposit in the phantom

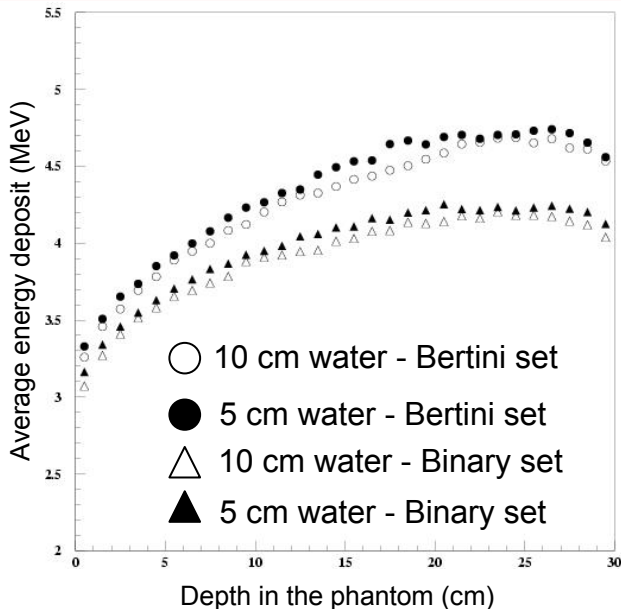
	5 cm water	10 cm water
EM + Bertini	130.2 ± 0.5	128.0 ± 0.5
EM + Binary	119.3 ± 0.4	117.3 ± 0.4

Doubling the shielding thickness results in:

- **Few % difference** in the stopped GCR protons
- **~2 % difference** in the total energy deposit



Average energy deposit of GCR p in the phantom

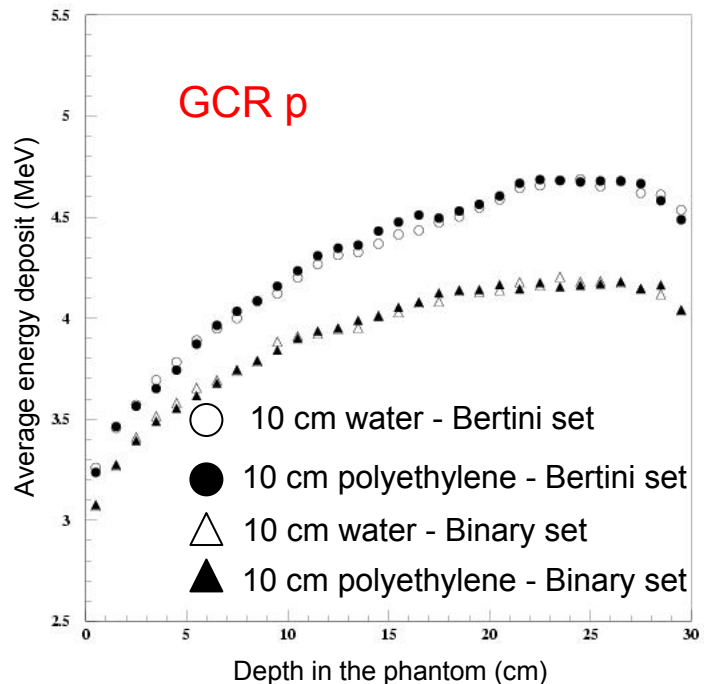


Shielding material for an inflatable habitat

Polyethylene

Water

Average energy deposit of GCR p



Energy deposit in the phantom (MeV)

10 cm polyethylene

10 cm water

EM + Bertini

128.4 ± 0.5

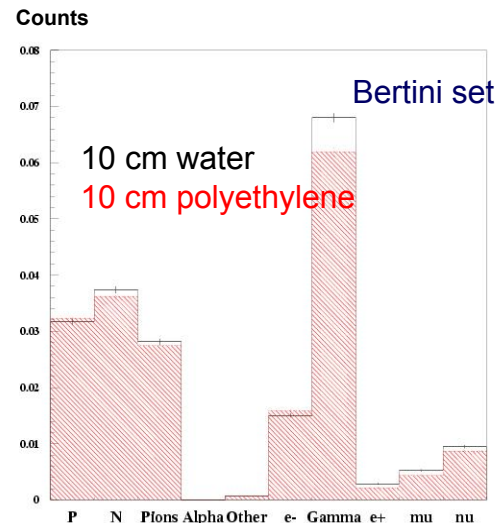
128.0 ± 0.5

EM + Binary

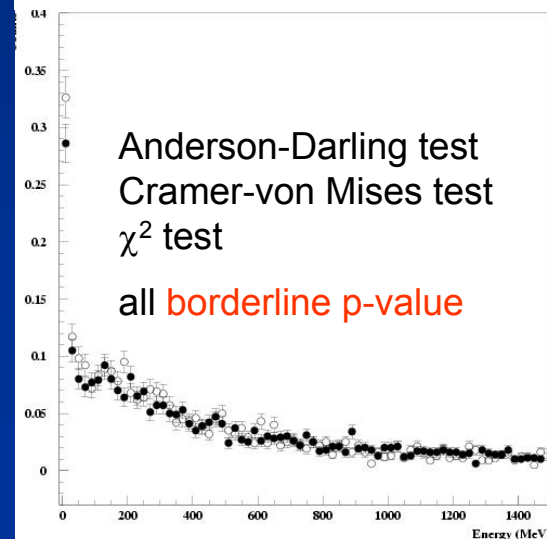
117.3 ± 0.5

117.3 ± 0.5

Average number of secondary particles reaching the phantom



Energy of secondary n

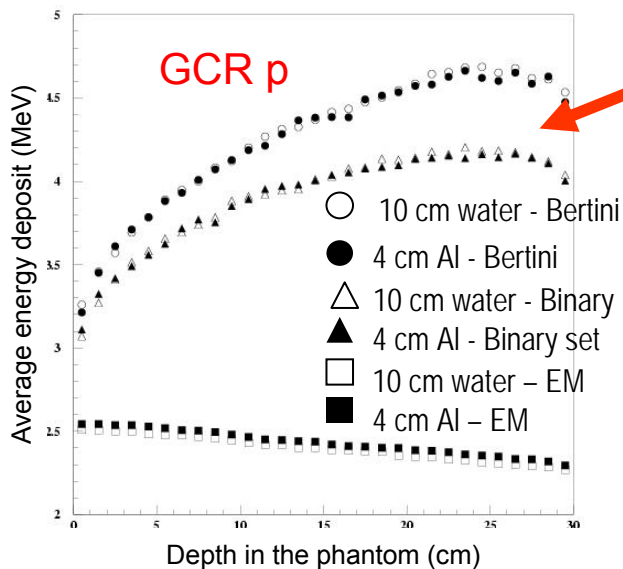


**Water and polyethylene:
equivalent shielding effect**

Inflatable vs. Rigid Habitat

Reference: rigid structures as in the ISS (2 - 4 cm Al)

Average energy deposit of GCR p



Kolmogorov-Smirnov test

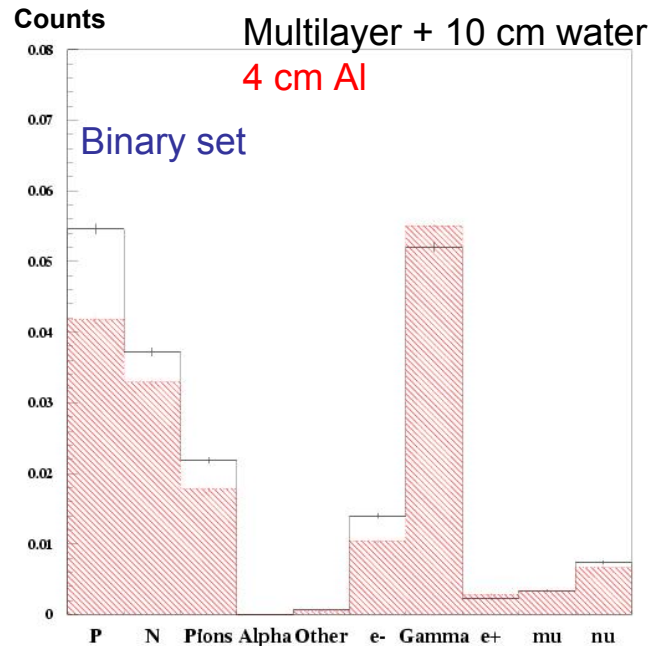
- Multi-layer + 10 cm water equivalent to 4 cm Al
- Multi-layer + 5 cm water equivalent to 2.15 cm Al

Shielding material	Energy deposited in phantom (MeV)		
	EM	Bertini	Binary
ML + 5 cm water	73.5 ± 0.3	130.2 ± 0.5	119.3 ± 0.4
ML + 10 cm water	71.9 ± 0.3	128.0 ± 0.5	117.3 ± 0.5
4 cm Al	72.9 ± 0.3	127.5 ± 0.5	117.0 ± 0.4
2.15 cm Al	73.9 ± 0.3	130.5 ± 0.5	119.3 ± 0.5

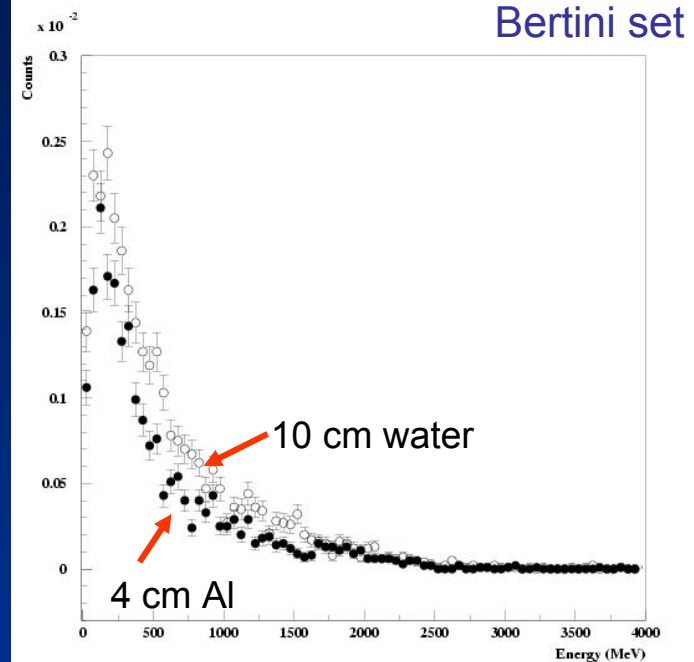
An inflatable habitat exhibits a shielding capability equivalent to a conventional rigid one

Secondary products in inflatable and rigid habitats

Average no. of secondary particles reaching the phantom



Energy spectrum of secondary protons



Anderson-Darling test
Cramer-von Mises test
 χ^2 test



Different

No significant effects on the energy deposit in the phantom

Effects of other cosmic ray components

Similar studies of GCR α , C, O, Si and Fe ion components

Energy deposited in phantom (MeV) by GCR α
Weighted according to the relative flux w.r.t. p

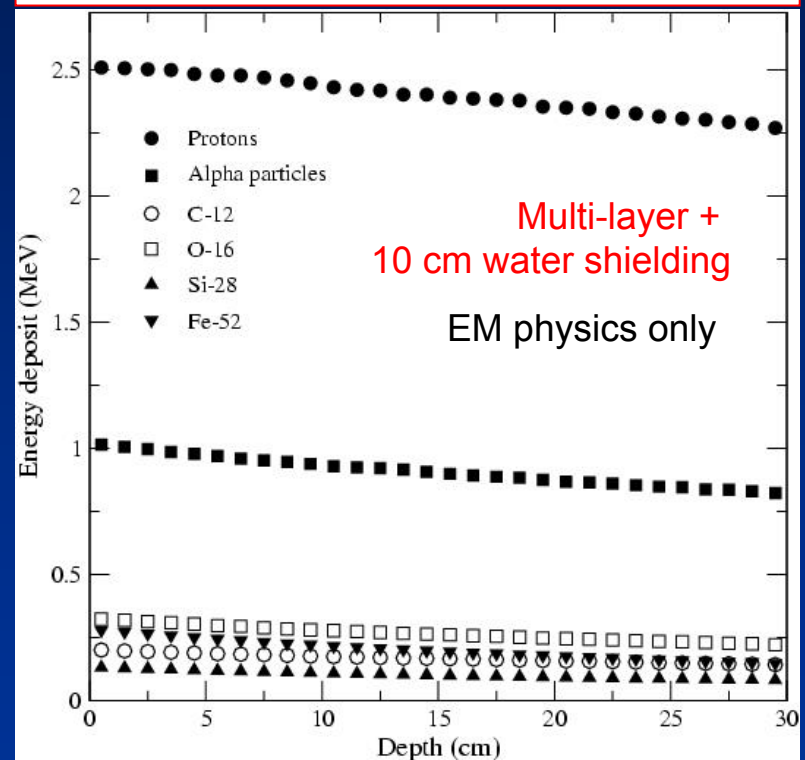
	Multi-layer + 10 cm water
EM	27.2 \pm 0.1
EM + Bertini	32.0 \pm 0.1
EM + Binary	31.7 \pm 0.1

Dominant contribution derived from
electromagnetic interactions

First indication

The hadronic models for α particles are under
development and under validation

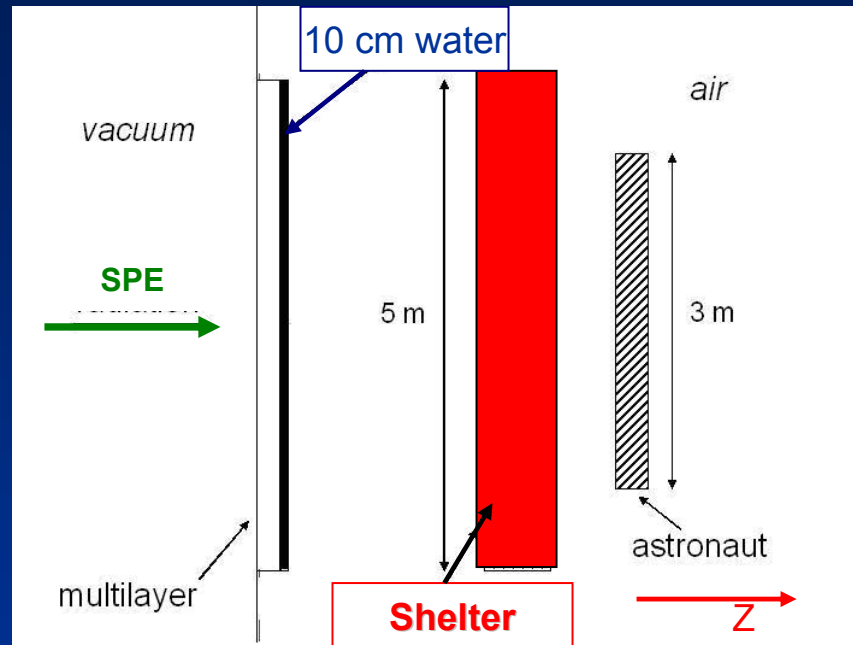
Average energy deposit of GCR ions
Weighted according to the relative flux w.r.t. p



Main contribution from p and α

Radiation protection from solar particle events

A shelter protects the crew from the harmful effects of solar particle events



Shelter: limited zone enclosed by an additional shielding layer

Alarm of a solar particle event

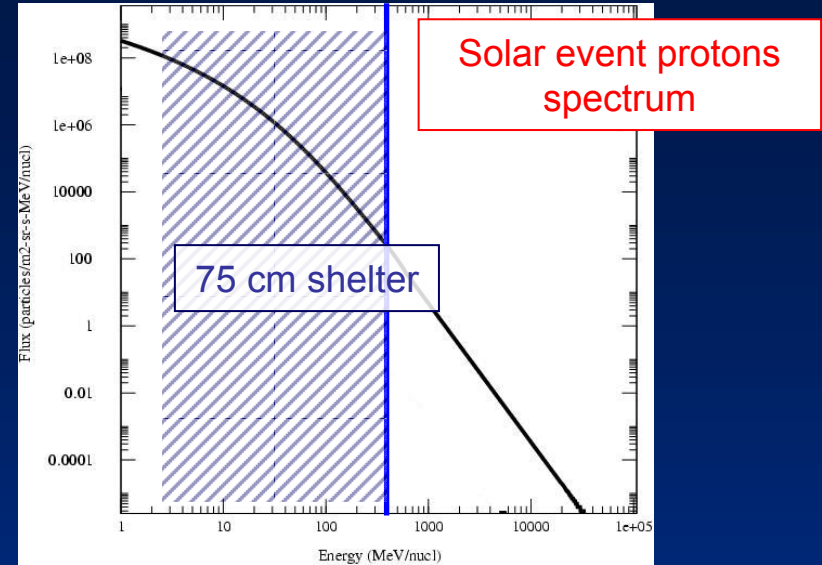


The astronauts recover in the shelter

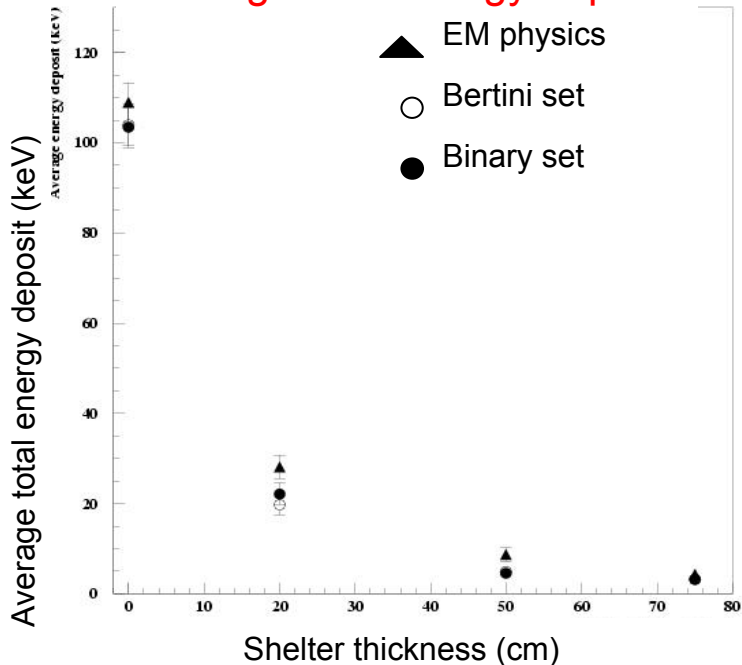
Solar particle events

Fraction of solar event protons reaching the phantom

Shelter thickness (cm)	%
0	$(1.03 \pm 0.05) 10^{-1}$
20	$(1.6 \pm 0.2) 10^{-2}$
50	$(3.4 \pm 0.8) 10^{-3}$
75	$(2.0 \pm 0.6) 10^{-3}$



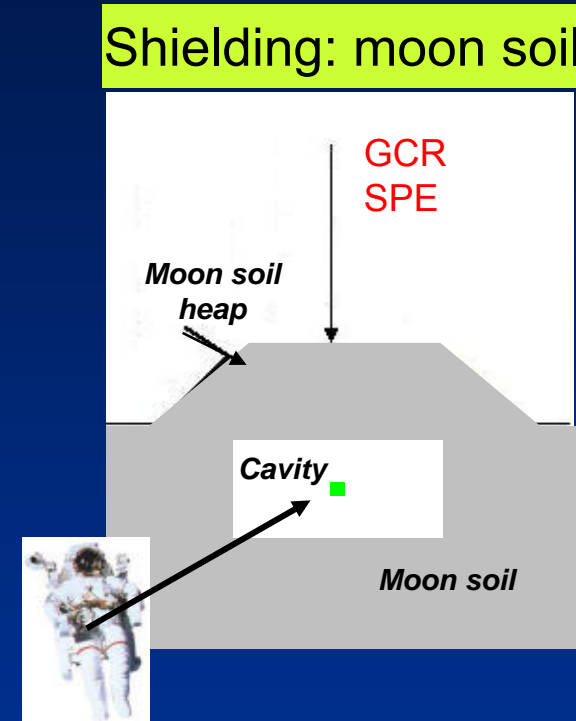
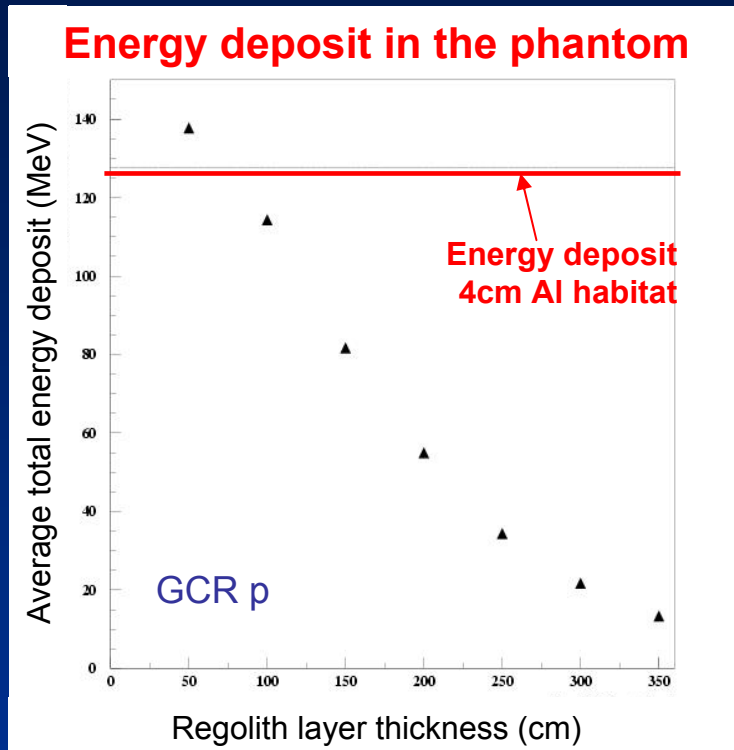
Average total energy deposit



An additional shelter layer is effective at stopping a significant fraction of solar particle events

Radiation shielding on planetary surface

Moon: intermediate step to a human mission to Mars



Shielding against GCR

Lunar regolith shielding is comparable to or better than a conventional Al structure

Shielding against SPE

50 cm regolith equivalent to the shielding effectiveness of 50 cm SPE vehicle shelter

Summary

● Inflatable Habitat + shielding

- Hadronic interactions are significant, systematics is under control
- The shielding capabilities of an inflatable habitat are comparable to a conventional rigid structure
- Water / polyethylene are equivalent
- Shielding thickness optimisation involves complex physics effects
- An additional shielding layer, enclosing a special shelter zone, is effective against SPE

● Moon Habitat

- Regolith shielding limits GCR and SPE exposure effectively
- Its shielding capabilities against GCR can be better than conventional Al structures as in the ISS

Conclusions

- This project represents the **first attempt in the European AURORA programme** to estimate the radiation protection of astronauts quantitatively
 - Quantitative evaluations
 - Based on open source, validated software
 - Guidance to space industry
- The software system developed is **publicly available** to the scientific community
 - Advanced software technology
 - Open to extension and evolution
- **1st development cycle of a long-term project** in collaboration with ESA

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