Modeling Martian Muon Flux and Subsurface Attenuation: Assessing the Feasibility of Muography in Lava Tubes

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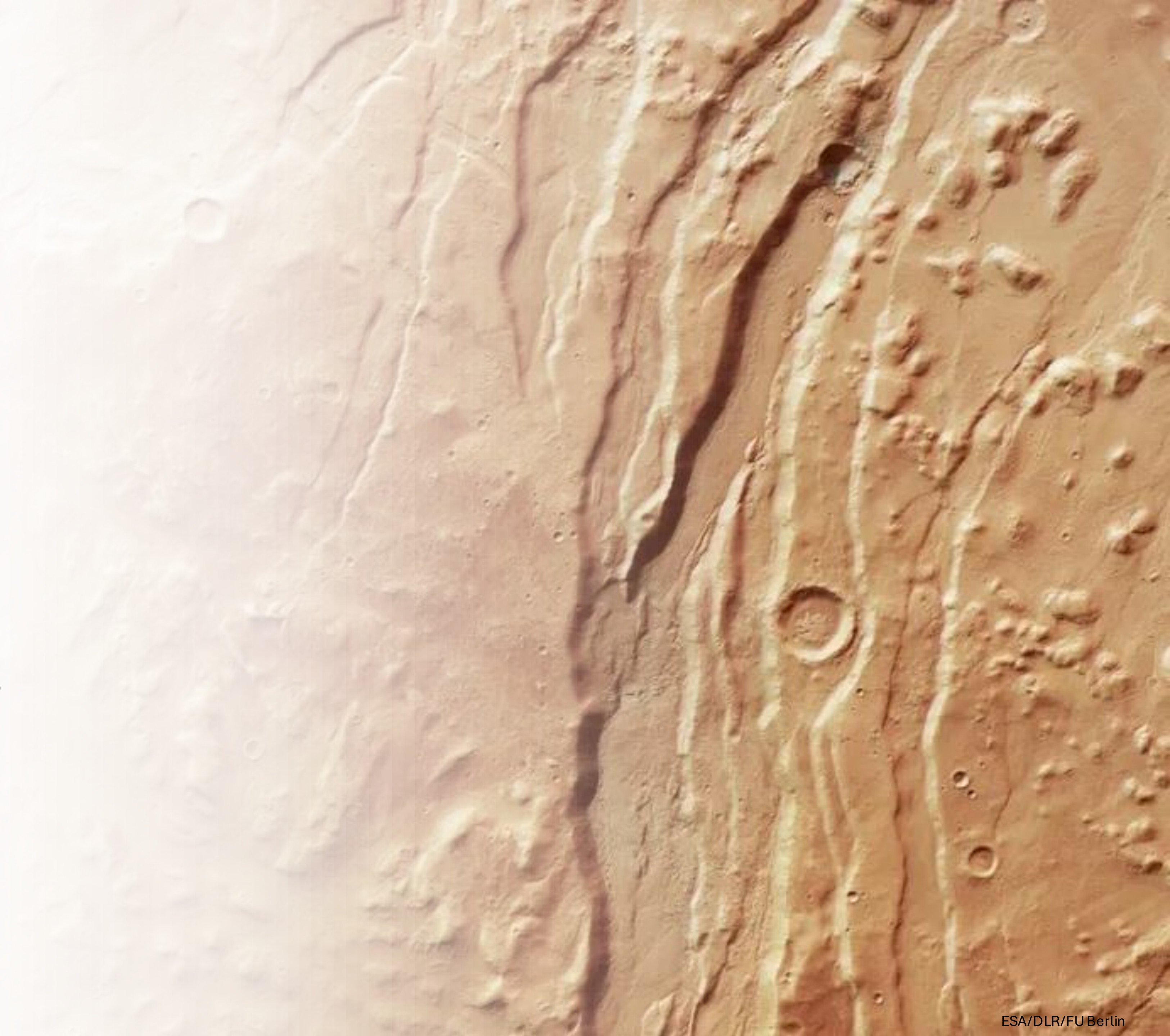

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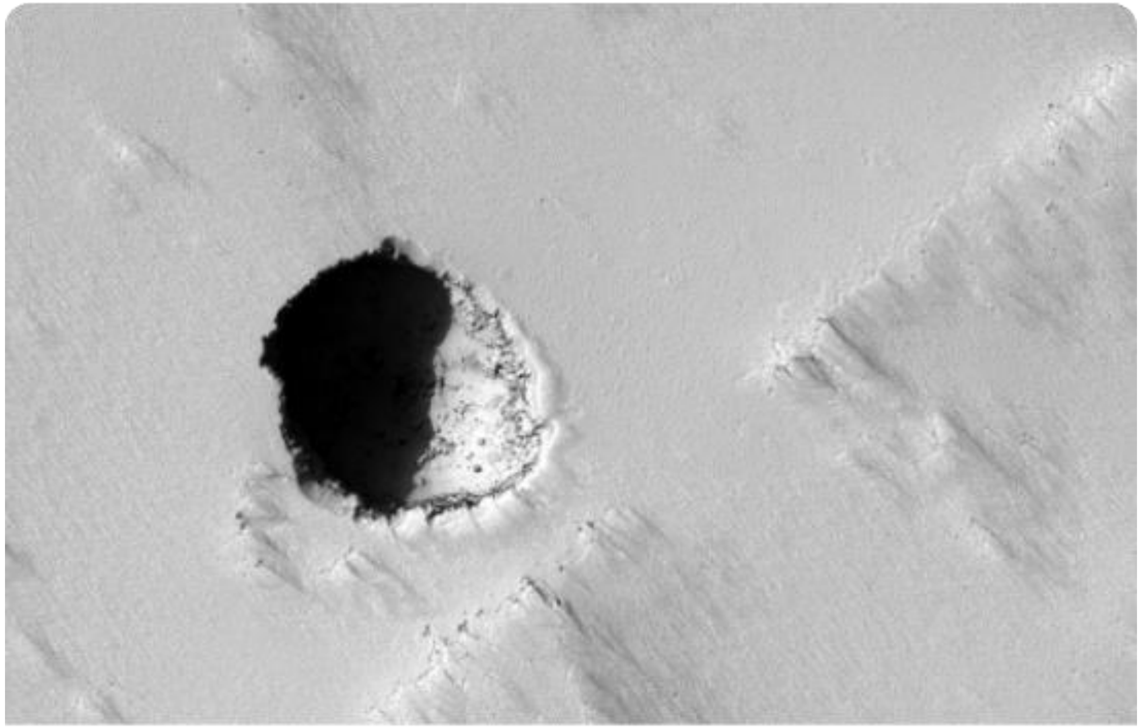
Outline

- Scientific Motivation
- The Martian environment challenge
- Atmospheric Cascades and Radiation Environment
- Martian Atmospheric Modeling
- Simulation pipeline
- GCR Modelling and Primary Events
- Validation of the Computational Setup
- 3D Subsurface Model Framework
- Results
- Conclusions and future perspectives

Scientific Motivation

- **Planetary Muography:** Non-invasive imaging of thickness and density of large-scale geological formations.
- **Human Exploration:** Characterization of potentially habitable subsurface environments and key insights for future mission planning.
  - **Radiation Dose Assessment**: Numerical simulations conducted to estimate the cosmic radiation doses received by future astronauts inside subsurface structures.
- **Primary Targets:** Voluminous underground caves and lava tubes (roofs >10m).
- **Natural Shelters:** Subsurface habitats providing critical shielding against Martian surface hazards:
  - Cosmic & solar radiation
  - Micrometeorites & dust storms
  - Extreme temperature fluctuations & winds



The Martian environment challenge

- **Atmospheric Pressure:** On Mars, the surface pressure is only **6–7 hPa** (< 1% of Earth's 1013 hPa).
- **Composition:** A thin atmosphere strictly dominated by **CO_2** (~95%).
- **Magnetic Field:** Absence of a global intrinsic magnetosphere leads to direct exposure to **Galactic Cosmic Rays (GCR)**.
- **The Physical Impact:** This extreme environment drastically modifies the development of secondary particle cascades compared to Earth.

	Earth	Mars
Surface Pressure	1013 hPa	**~6–7 hPa**
Atmosphere	N2, O2 dominated	**CO2 dominated**
Global Magnetosphere	Present (✓)	**Absent (✗)**

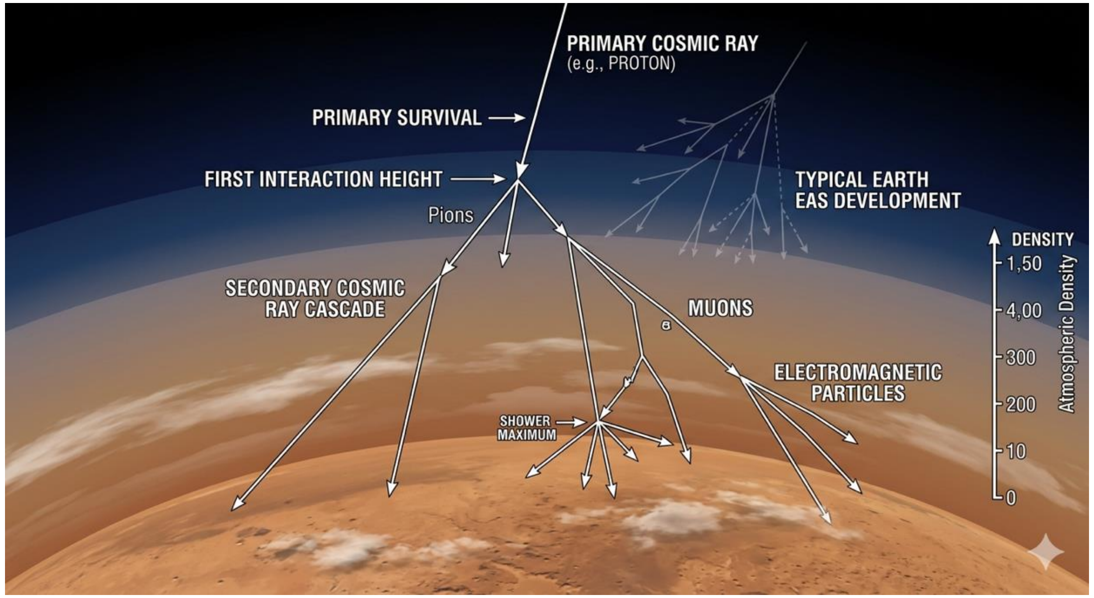
Atmospheric Cascades and Radiation Environment

Altered EAS Development

- **"Squashed" Showers:** Low density (~1% of Earth) shifts the first interaction and shower maximum much closer to the ground.
- **Primary Survival:** The thin atmosphere allows a high fraction of primary particles to reach the ground, creating significant **surface noise**.

Solar Activity Modulation

- **Solar Minimum:** Minimum heliospheric shielding → **Peak muon flux** (higher background interference) .
- **Solar Maximum:** Stronger GCR shielding, but high risk of Solar Particle Events (SEP).



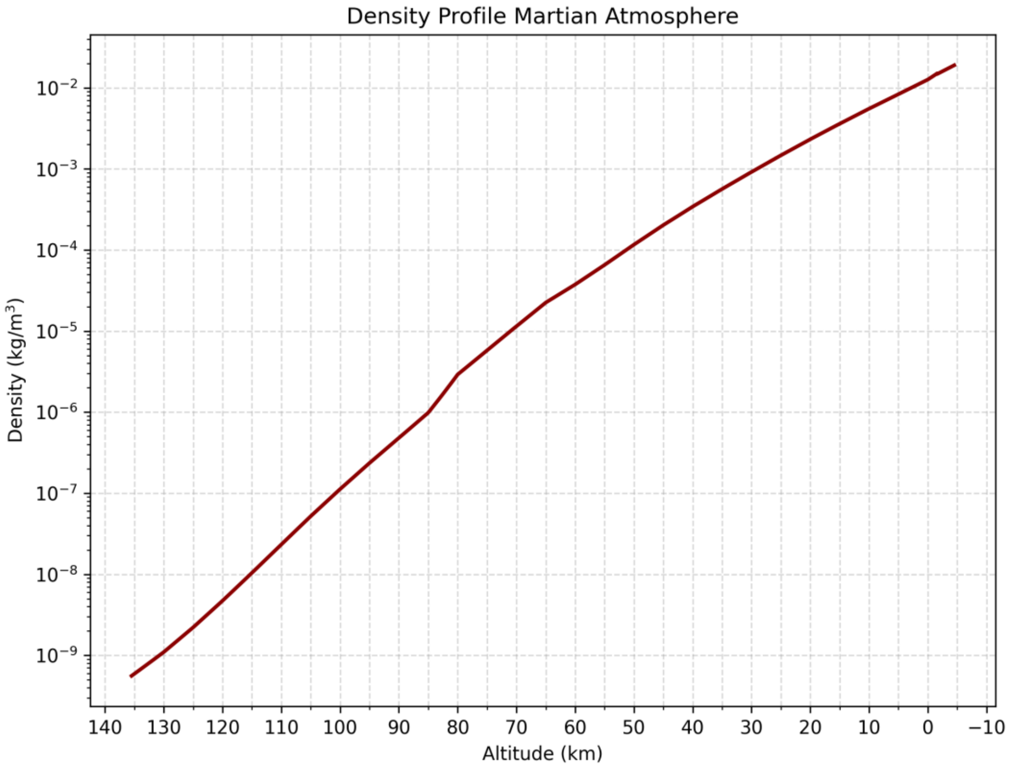
__Scientific Context:__ While MSL/RAD provides essential total dose data, direct high-precision measurements of the __muon flux__ on the surface are currently missing.

Martian Atmospheric Modeling

Based on the **Mars Global Reference Atmospheric Model** 2024 (MarsGRAM-24)

Parameters:

- **Position:** Gale Crater (depth 4.5 km)
- **Latitude**: 5.4 °S
- **Longitude**:137.8 °E
- **Total atmospheric thickness**: 120 km (~ 22 g/cm^2)
- **Composition:**
  - 95.32% CO_2,
  - 2.7% N_2,
  - 1.6% Ar,
  - 0.13% O_2,
  - 0.07% CO,
  - 0.03 % H_2O.
- **Reference Period:** Simulated data corresponding to the Martian Year 31 (2012–2013).
- **Atmospheric Profile:** Mean profile derived from **Gale Crater** daily predictions, averaged over solstices and equinoxes.



Simulation Pipeline

Primary Flux

GCR proton input spectra based on solar activity conditions.

→

CORSIKA 8

Development of the atmospheric shower.

→

FLUKA

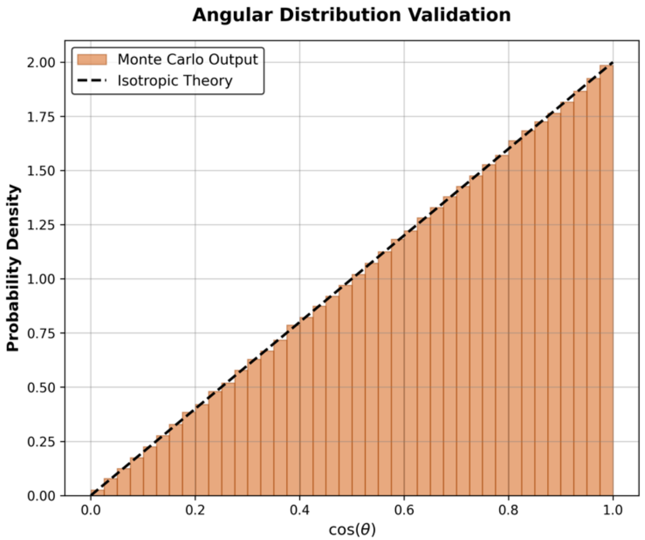
Detailed underground muon transport (regolith and basalt).

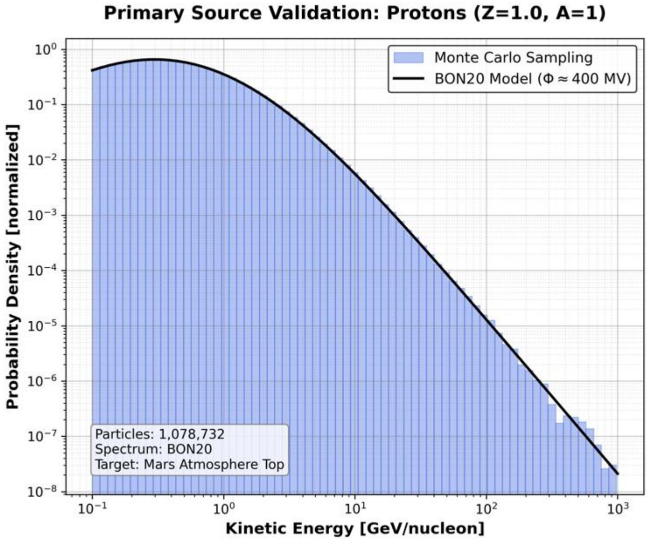
→

Final Flux

Energetic and angular characterization of the muon flux.

GCR Modelling and Primary Events





Primary Source Modelling

- **GCR Boundary Flux:** Energy spectra derived from the **BON20 model** via the **NASA OLTARIS tool** (Deep Space, 1 AU).
- **Solar Conditions:** Simulated under **Solar Minimum** conditions (Cycle 24, Φ = 400 MV) for a 1-year (365 days) reference mission.

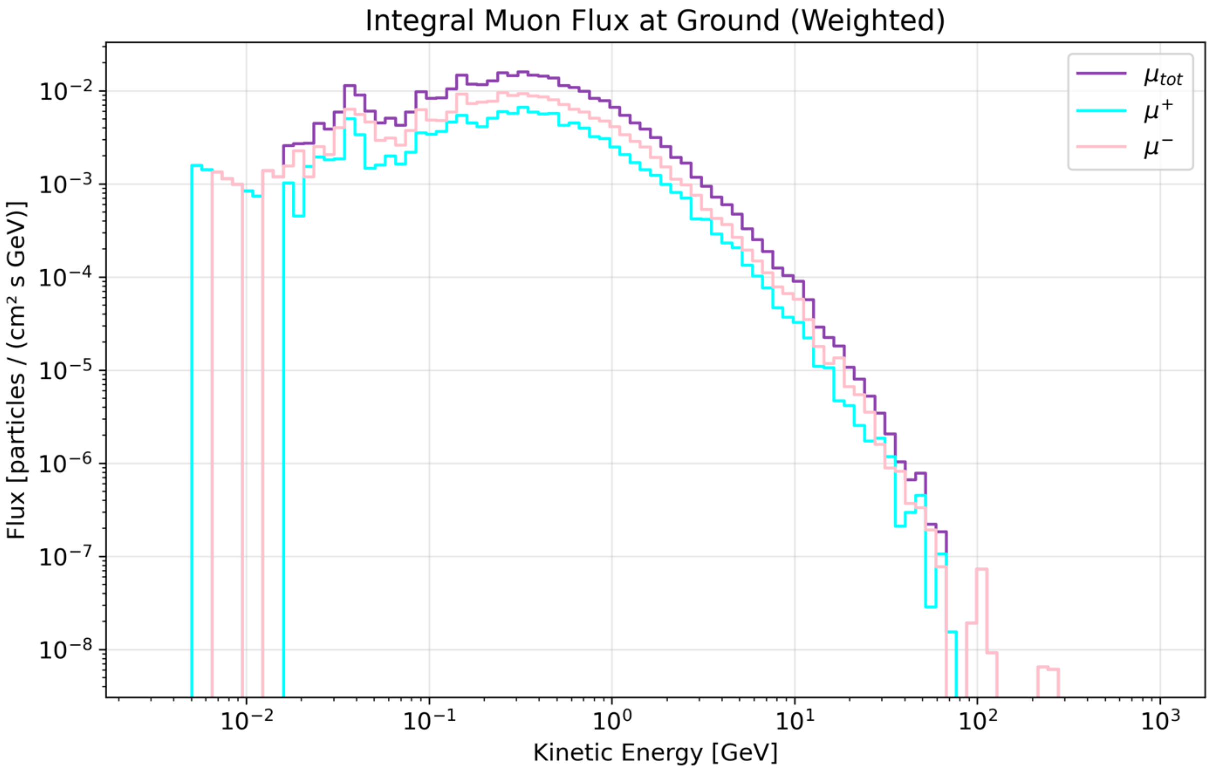
Flux & Sampling Configuration

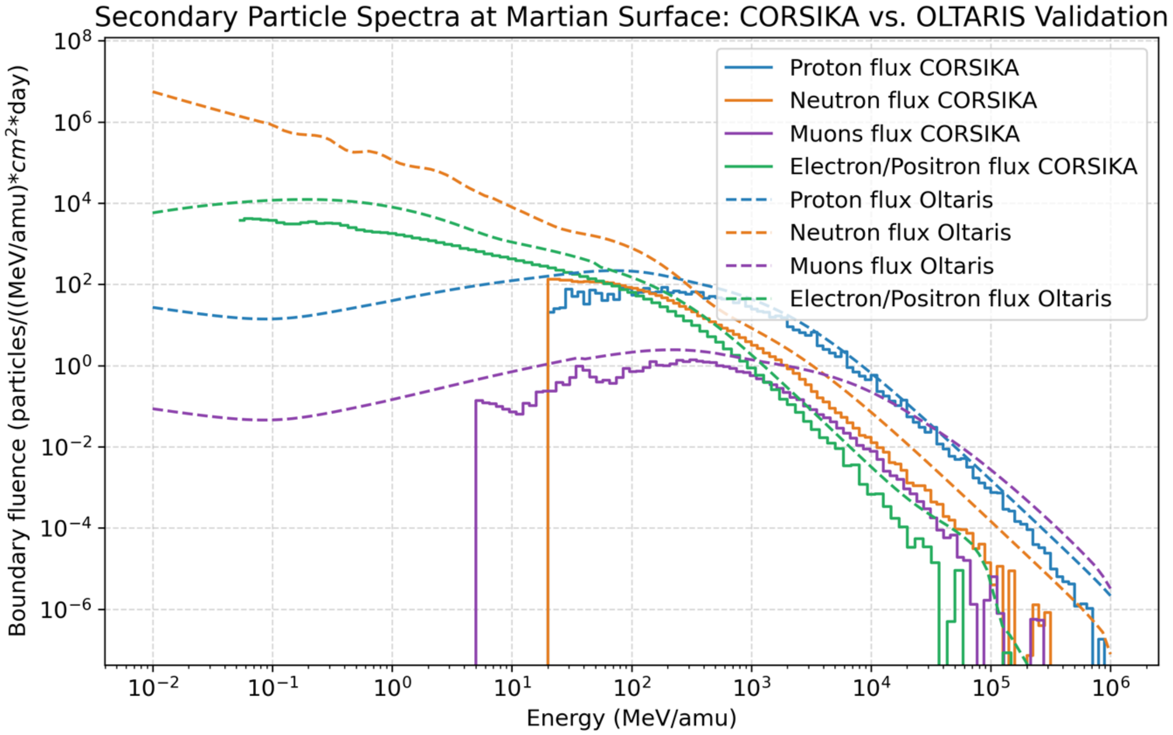
- **Monte Carlo Sampling:** 1×10^9 primary proton events independently sampled from the model spectra to define initial kinetic energies and zenith angles.
- **Angular Distribution**: Isotropic injection at the top of the Martian atmosphere.
- **Binning Resolution:** Sampled events grouped into precise energy (ΔE∼10%) and zenith angle (Δθ = 10°) bins.
- **Kinetic Energy Cutoff:** Minimum threshold for primary protons set at **0.10 GeV.**

Simulation Core

- CORSIKA 8 setup tailored for Martian atmospheric density profile.
- **Hadronic Interaction Models**: SIBYLL 2.3d for high-energy interactions (E>63.1 GeV)/ FLUKA for low-energy ones
- **Validation Framework:** Ground-level simulation outputs are subsequently **benchmarked against OLTARIS surface predictions** to validate the atmospheric transport.

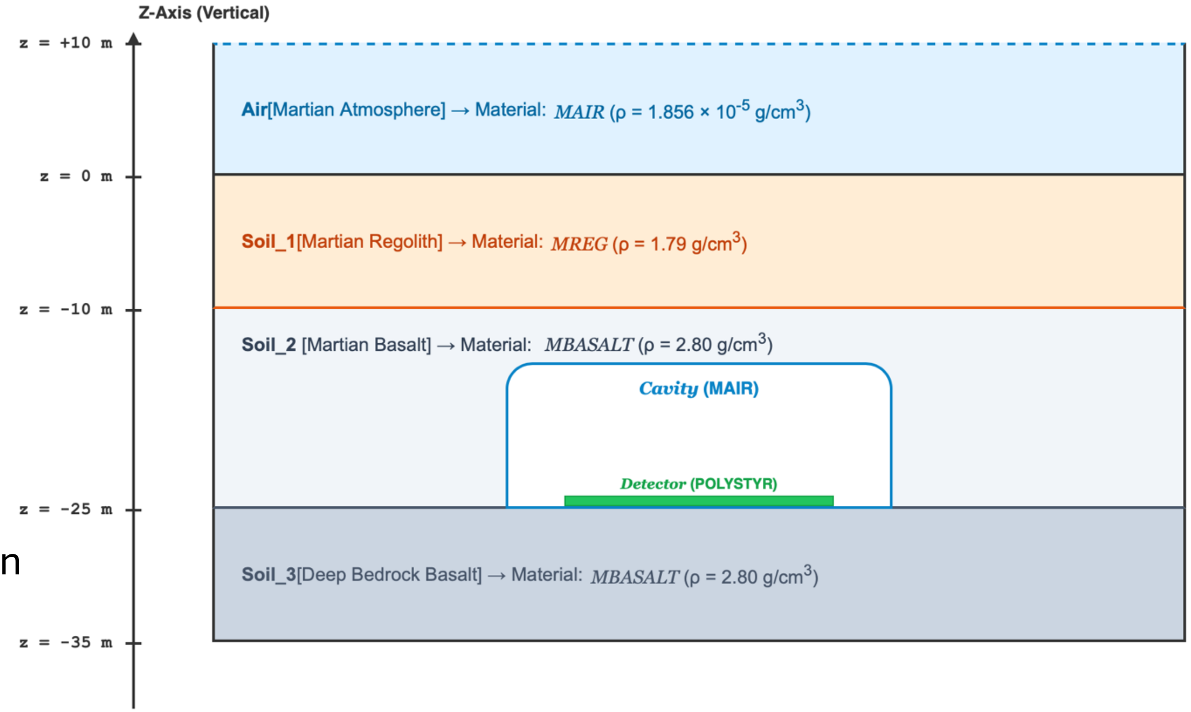
Validation of the Computational Setup





3D Subsurface Model Framework

- **Martian Regolith :** Extends from surface (z = 0) down to z = -10m ($\rho = 1.79\ g/cm^3$).
- **Martian Basalt:** Extends from z = -10 m down to z = -35 m ($\rho = 2.80\ g/cm^3$).
- **Lithological Boundary:** A sharp material discontinuity is implemented at z = -10 m to decouple the porous regolith from the dense basalt matrix.
- **Cylindrical Cavity (Cavity):** A volcanic lava tube modeled via a horizontal RCC body (Radius = 10 m) filled with low-density Martian atmosphere ($\rho = 1.856 \times 10 - 5\ g/cm^3$).
- **Detector Setup :** A plastic scintillator tile (10 m × 10 m, 10 cm thickness, POLYSTYR), placed exactly on the cave floor (z = -25 m) to record the survival muon flux.



Methodology: The muographic signal is isolated by directly comparing the flux simulated inside the cavity with a reference baseline simulation of solid and homogeneous soil.

Optimized Subsurface Muon Transport

Muon-only Injection

Only the muon component validated at the surface is propagated into the soil as a first conservative approximation to optimize computational weight.

Spatial Randomization

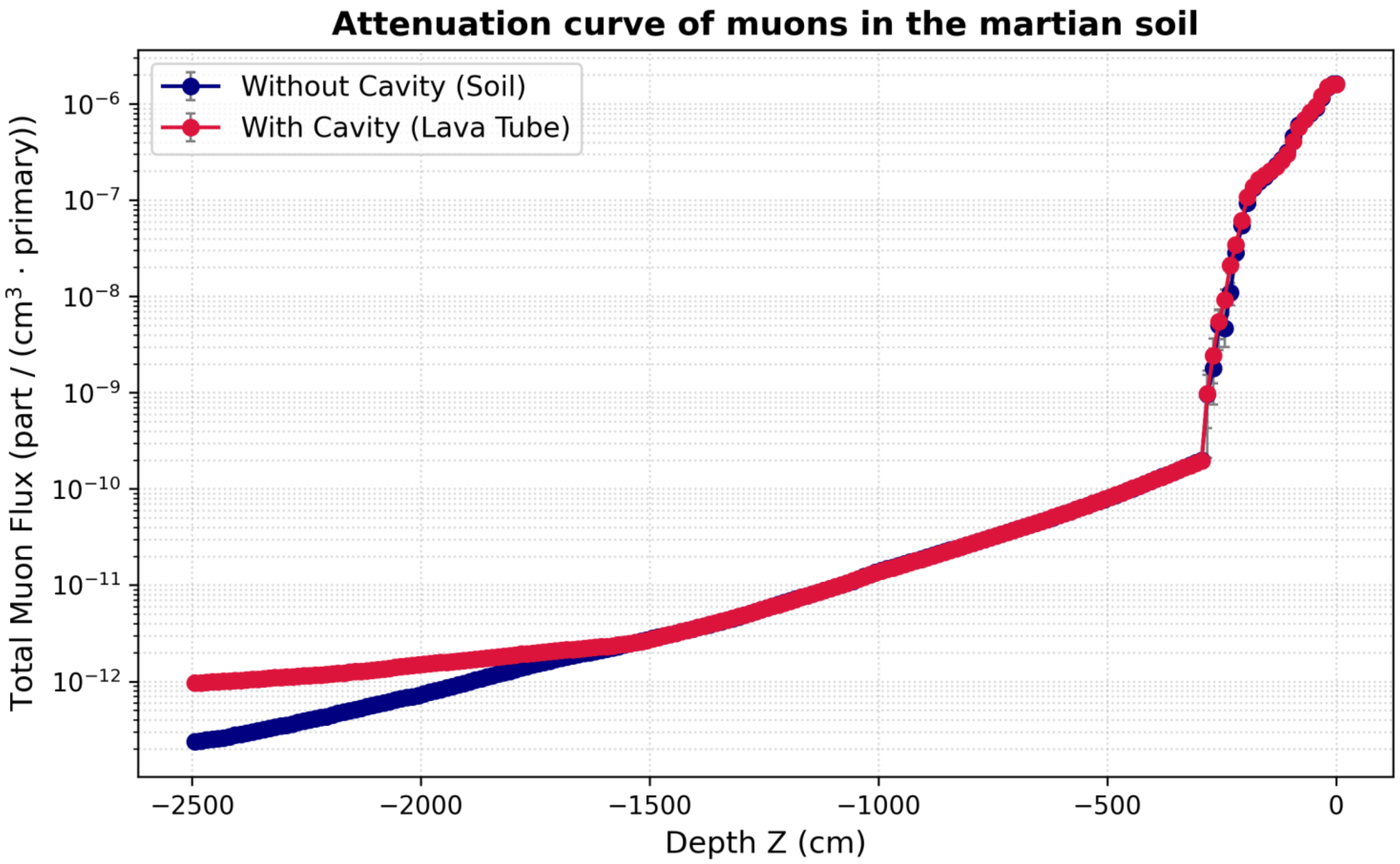
Primary events are spatially randomized over a 10x10m planar source centered above the cavity, ensuring uniform illumination of the subsurface model.

Flux Oversampling

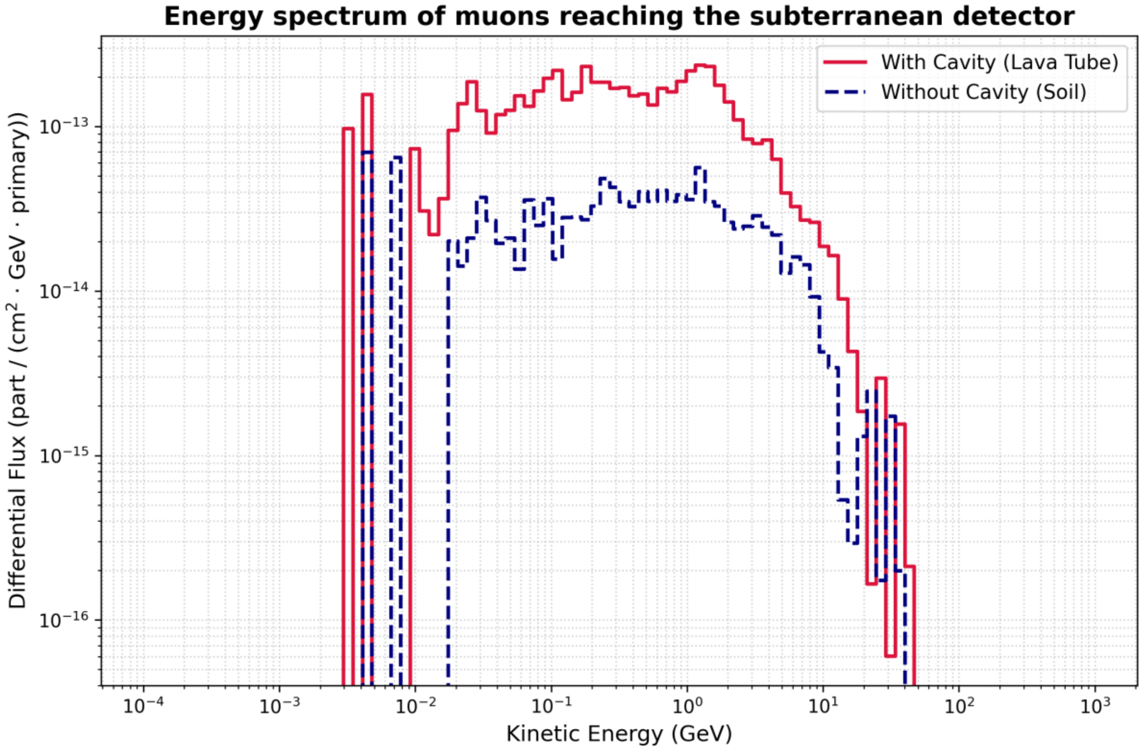
The same surface energy-angle distribution is sampled multiple times to increase event statistics in the small detector volume (10^7 events)

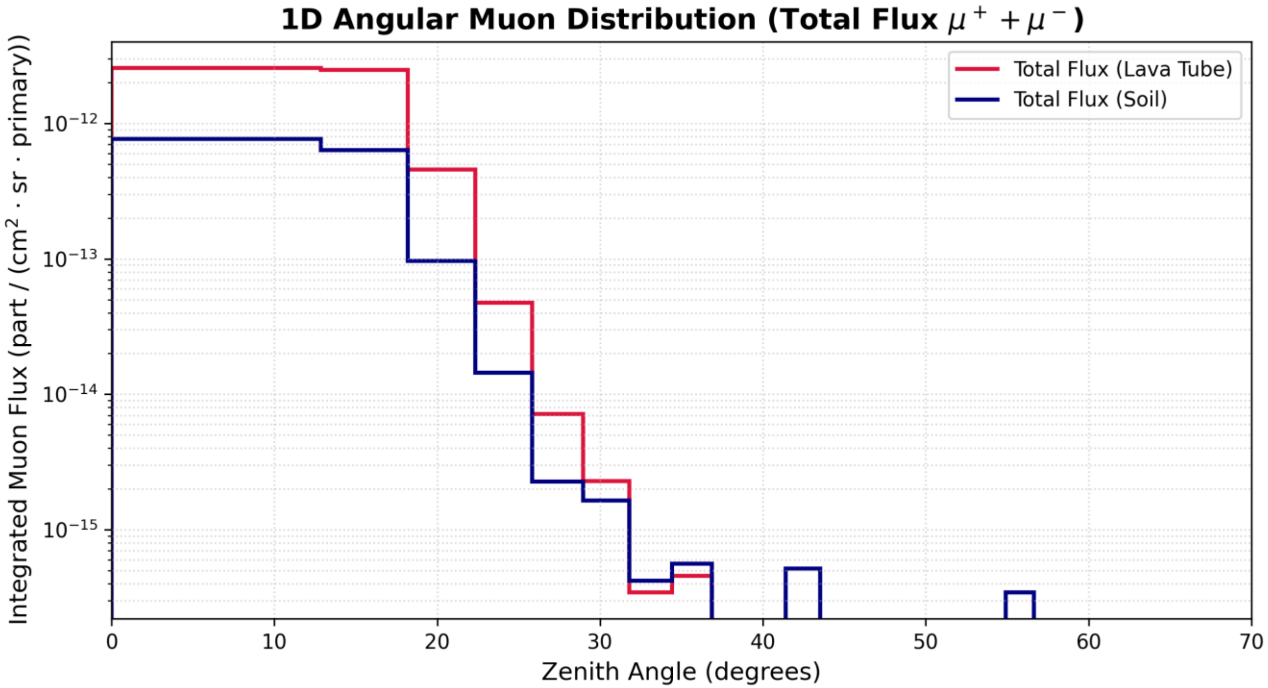
Results

- **Flux vs Depth**: Muon flux behavior modeled from the Martian surface down to -2500 cm.
- **The Cavity Effect:** Above -1500 cm, both curves overlap perfectly as muons traverse homogenous soil.
- **Divergence at Depth:** Below -1500 cm, the With Cavity (Lava Tube) flux is significantly higher due to reduced rock attenuation



Results





- **Energy Distribution:** Differential kinetic energy spectrum of muons reaching the underground target.
- **Broad Flux Enhancement:** The With Cavity scenario (red line) shows a consistently higher flux across the main energy range (~0.01 to 10 GeV).
- **Reduced Energy Loss:** The void of the lava tube significantly reduces the stopping power of the environment, preserving a more intense muon spectrum

- **Zenith Angle Distribution:** Comparison of the angular distribution reaching the deep detector.
- **Signal Window:** A clear flux enhancement is visible at low zenith angles (**0° to 25°**).
- **Radiography Potential:** The cosmic muon excess highlights the capability of resolving the lava tube shape from underground measurements.

Conclusions and future perspectives

Conclusions

- **Validated Atmospheric Baseline**: The generation and transport of secondary particles through the Martian atmosphere have been successfully benchmarked, showing good agreement with analogous calculation codes, thus establishing a reliable input for subsurface modeling.
- **Clear Cavity Signature:** The lava tube structural void produces a distinct divergence in the attenuation curve below **15 m** of depth.
- **Directional & Energy Excess:** The signal is characterized by a significant flux enhancement at low zenith angles (**0° to 25°**) and a well-preserved energy spectrum between **0.01 and 10 GeV**.

Future perspectives

- **Primary Source Expansion:** Incorporation of the full Galactic Cosmic Ray (GCR) spectrum
- **Detector Optimization:** Evaluate different tracking technologies, geometric configurations, and angular resolutions for the underground detector.
- **Background & Noise Analysis:** Simulate secondary particle scattering and environmental background noise to refine the signal-to-noise ratio.
- **Sensitivity Mapping:** Test the model against varying cavity shapes, depths, and complex multi-layer Martian regolith compositions.

References

1. Alameddine, J.-M. et al. CORSIKA 8. Zenodo https://doi.org/10.5281/zenodo.15525791 (2025).
2. Alameddine, J. M. et al. Simulating radio emission from particle cascades with CORSIKA 8. Astroparticle Physics 166, (2025).
3. Engel, R. et al. Towards A Next Generation of CORSIKA: A Framework for the Simulation of Particle Cascades in Astroparticle Physics. Comput. Softw. Big Sci. 3, (2019).
4. Battistoni, G. et al. Overview of the FLUKA code. Ann. Nucl. Energy 82, 10–18 (2015).
5. Donadon, A. et al. FLAIR3 - recasting simulation experiences with the Advanced Interface for FLUKA and other Monte Carlo codes. EPJ Web Conf. 302, 11005 (2024).
6. Ahdida, C. et al. New Capabilities of the FLUKA Multi-Purpose Code. Front. Phys. Volume 9-2021, (2022).
7. Singleterry, R. C. et al. OLTARIS: On-line tool for the assessment of radiation in space. Acta Astronaut. 68, 1086–1097 (2011).
8. Slaba, T. ~C. & Whitman, K. The Badhwar-O’Neill 2020 GCR Model. Space Weather 18, e02456 (2020).
9. Justh, H. L. et al. Mars Global Reference Atmospheric Model (Mars-GRAM) 2024: User Guide. 12934 Preprint at (2024).

Thank You!

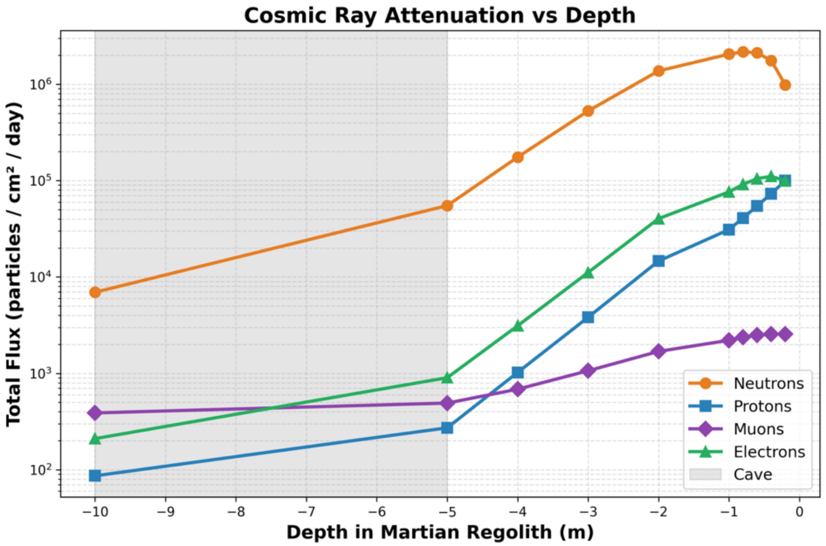
BACKUP

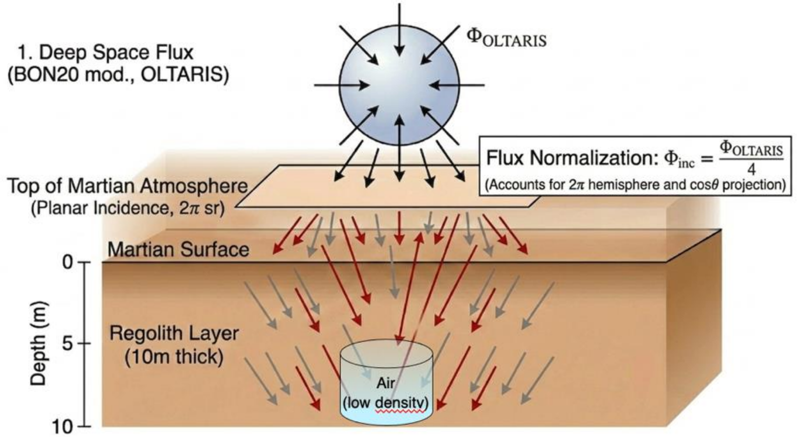
Soil and atmospheric composition

	Martian Regolith	**Martian Basalt**	**Martian Atmosphere**
Density	**1.79 g/cm^3**	**2.80 g/cm^3**	**1.856×10^{-5} g/cm^3**
Oxygen (O)	44.009%	45.000%	63.720%
Silicon (Si)	22.271%	23.000%	—
Iron (Fe)	18.092%	10.000%	—
Calcium (Ca)	5.771%	9.000%	—
Aluminum (Al)	5.540%	8.000%	—
Magnesium (Mg)	4.316%	5.000%	—
Carbon (C)	—	—	31.810%
Nitrogen (N)	—	—	2.850%
Argon (Ar)	—	—	1.600%
Hydrogen (H)	—	—	0.020%

Particle Attenuation in Martian Regolith

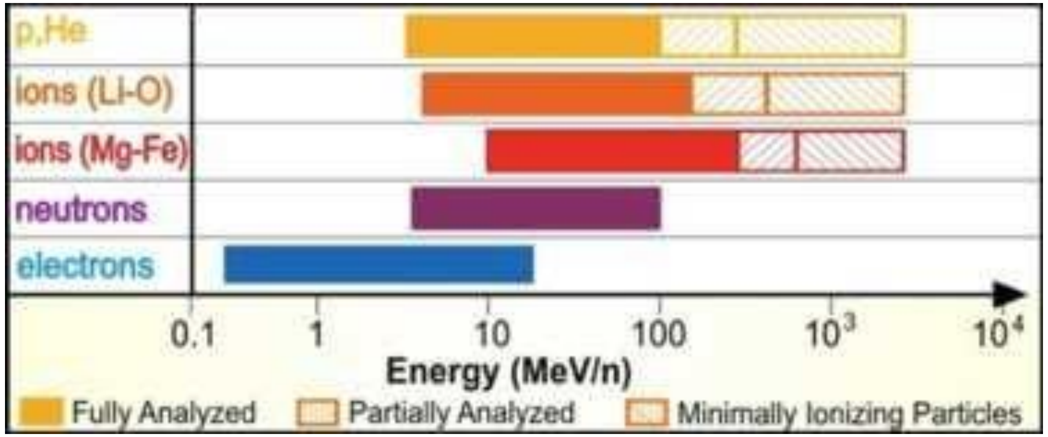
- **Source modelling:** GCR primary protons spectrum sampled from the BON20 model under moderate solar modulation (Φ = 577 MV).
- **Atmospheric model:** MarsGram 2024 (Gale Crater: alt. -4.5 km, atmospheric depth ~ 22 g/cm^2, 07/11/2012 at 12:00). Composition: 95.32% CO_2, 2.7% N_2, 1.6% Ar, 0.13% O_2, 0.07% CO, 0.03% H_2O.
- **Atmospheric transport:** Large-scale air showers simulated with CORSIKA 8 (3×10^5 events).
- **Subsurface Propagation:** Secondary particles reaching the surface are spatially randomized and injected into a FLUKA Monte Carlo model (10^6 events).
- **Soil parameters:** Regolith block (60×60m, 10 m depth) containing a cylindrical cavity (diameter 5m) at -5 m. Composition: 50% O, 40% Si, 10% Fe (density ρ = 1.79 g/cm^3).
- ***Conclusion:*** Muons exhibit the lowest attenuation rate among charged particles, confirming their suitability for deep subsurface imaging.



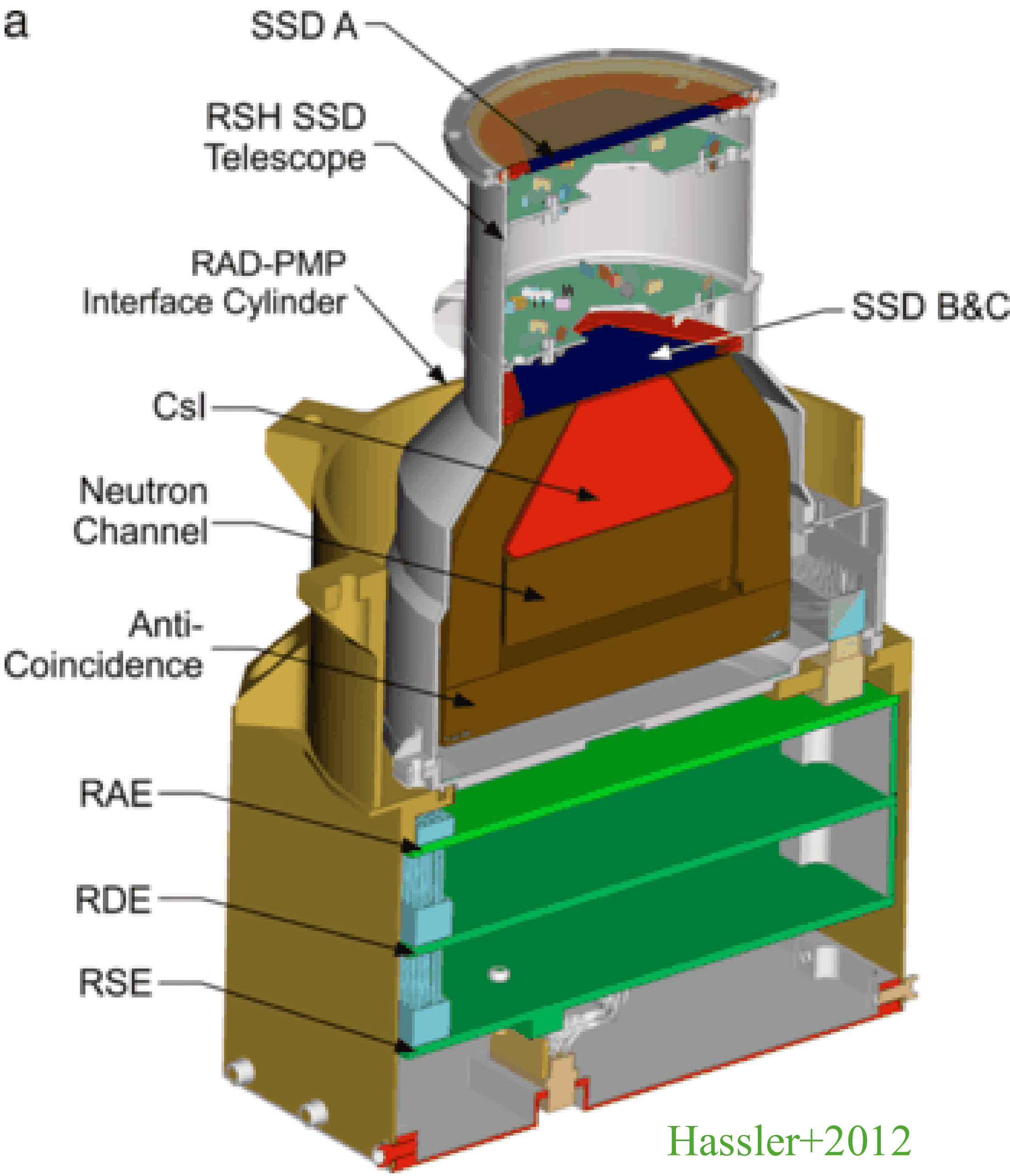


The Mars Science Laboratory Radiation Assessment Detector (MSL/RAD)

- Prime misure della radiazione sulla superficie di Marte
- Misure quasi interrotte dall’atterraggio del rover Curiosity nel cratere Gale (6 August 2012).
- Ha un ampio range dinamico per le particelle cariche ed è capace di misurare tutte le specie di ioni che contribuiscono alla radiazione
- Formato dal RAD Sensor Head (RSH) e dal RAD Electronics Box (REB) integrati insieme in un volume compatto.



RAD energy range e copertura per tipo di particella.



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