Modelling cosmic-ray propagation in electromagnetic fields and matter interactions with a Python package GT simulation

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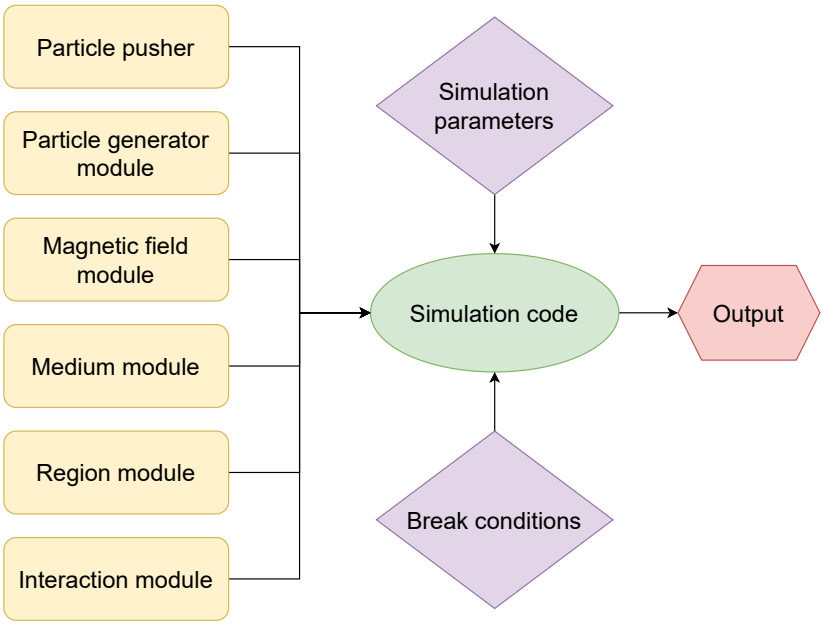
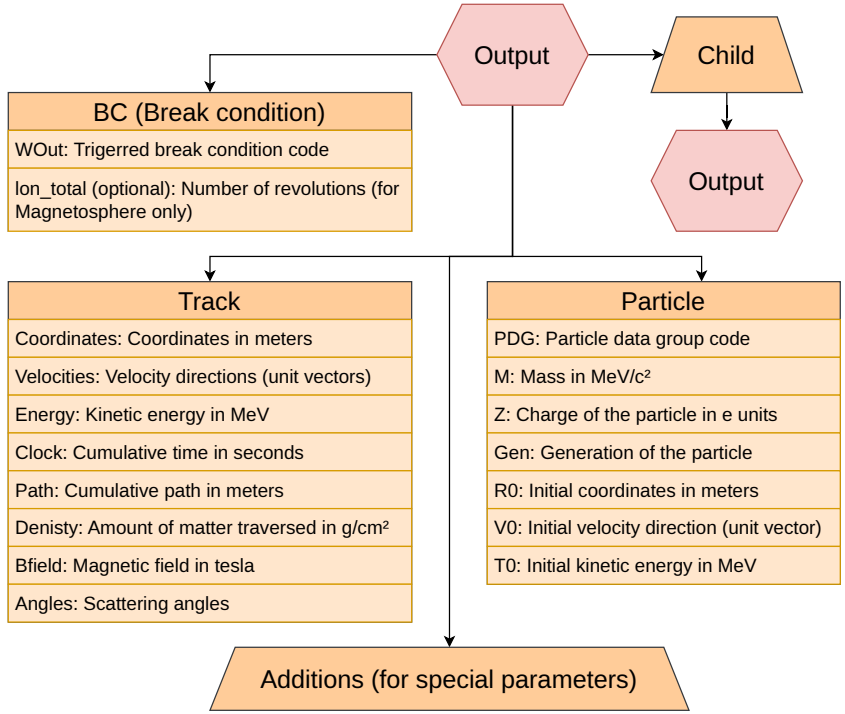
Simulation in cosmic ray physics

- Cosmic rays serve as a valuable source of information for astrophysics because they carry signatures of some of the most energetic processes in the Universe, including solar activity, supernova explosions, gamma-ray bursts, and many others.
- Experimental studies of cosmic rays often lack a complete theoretical interpretation and face numerous constraints.
- Several software tools have been developed to simulate cosmic ray propagation (GALPROP, CRPropa, HelMod)

GT package structure

Modules allow the user to describe or configure different aspects of the simulation.





Particle pusher module

Diffusive transport equation / stochastic equation of motion

$$\Downarrow$$

Relativistic equations of motion

$$\begin{cases} \dfrac{d\mathbf{r}}{dt} = \mathbf{v} \\ \dfrac{d(\gamma\mathbf{v})}{dt} = \dfrac{q}{m}\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \end{cases}$$

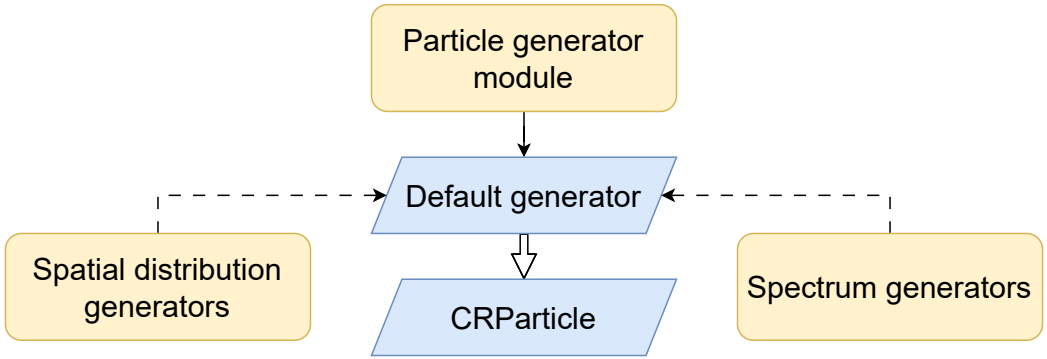
Numerical integration schemes:

- Runge-Kutta (4th, 6th order)
- Buneman-Boris,
- Vay, Higuera-Cary, etc.

Particle generator module

Spatial distribution:

- Uniformly on the surface of a sphere;
- Uniformly within a spherical or disk-shaped volume;
- User-specified array;



Spectral distribution:

- Uniform distribution;
- Monolines (fixed energy);
- Power spectrum (power-law distribution);
- Force-field spectrum (solar modulation losses);
- User-specified array;

Interdependent distribution:

- Pitch-angle generator (initial conditions depend on the magnitude of the magnetic field);

Magnetic field module

Magnetic field models can be either static or dynamic.

Earth's magnetosphere:

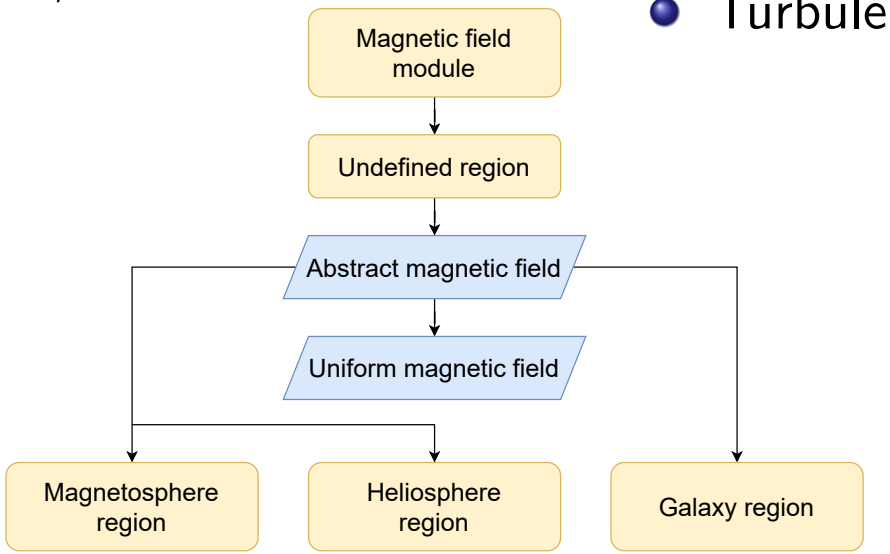
- Dipole field;
- IGRF-13, -14;
- Tsyganenko-89, -96, -15;
- CHAOS-7, -8;
- CM6;
- COV-OBS.x2;
- LCS-1;
- DIFI-6;

Heliosphere:

- Parker model;
- Turbulence field;

Galaxy:

- JF12;
- UF23;
- Turbulence field;



Medium module

Earth:

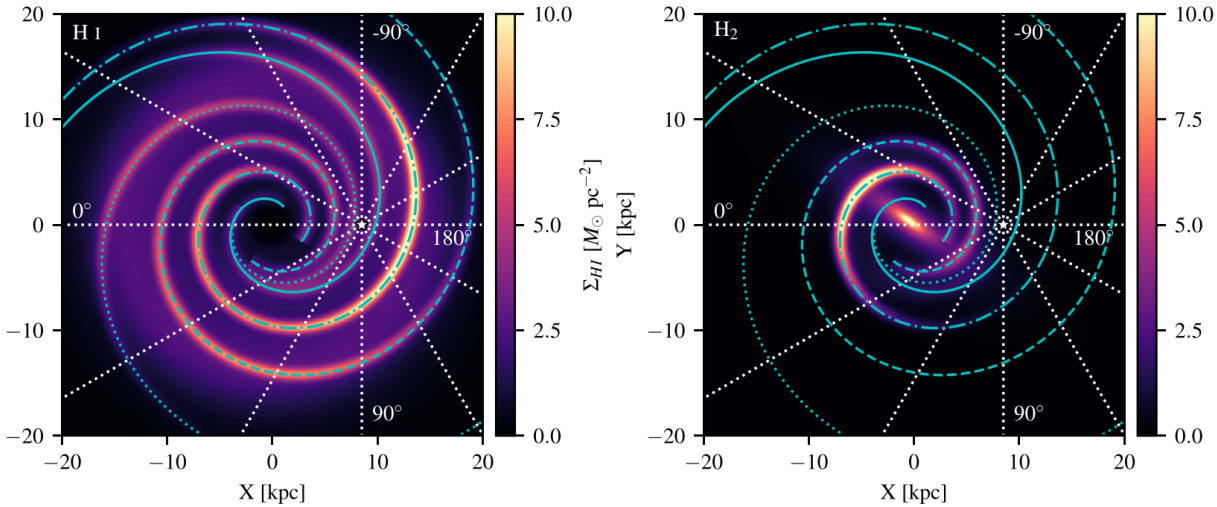
- NRLMSISE-00 (atmosphere);
- IRI-2016 (ionosphere);

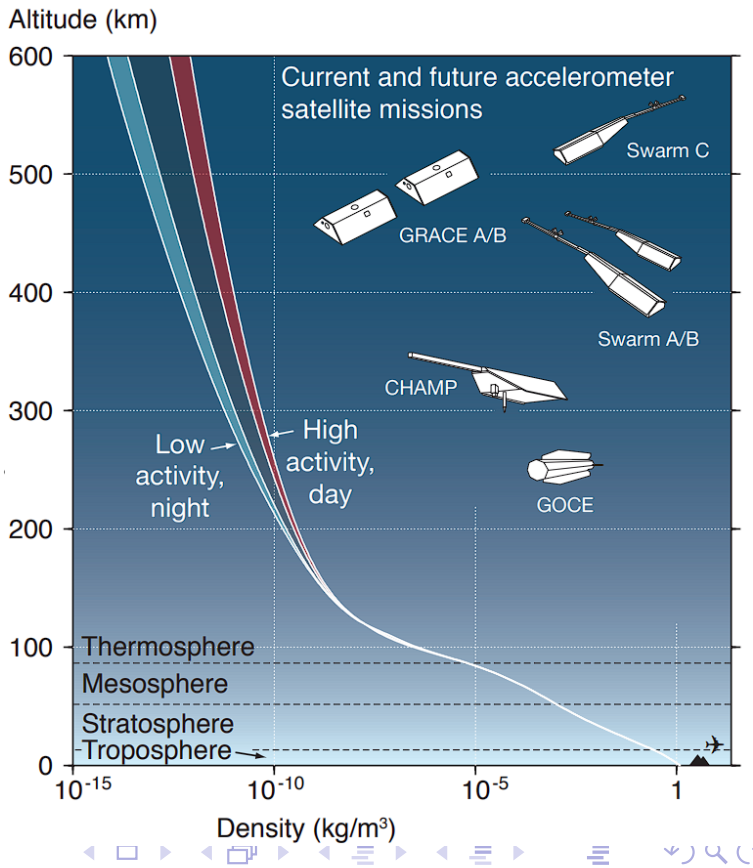
Galaxy:

- Model by Jóhannesson et al., ApJ (2018);

Total grammage accumulated by the CR particle:

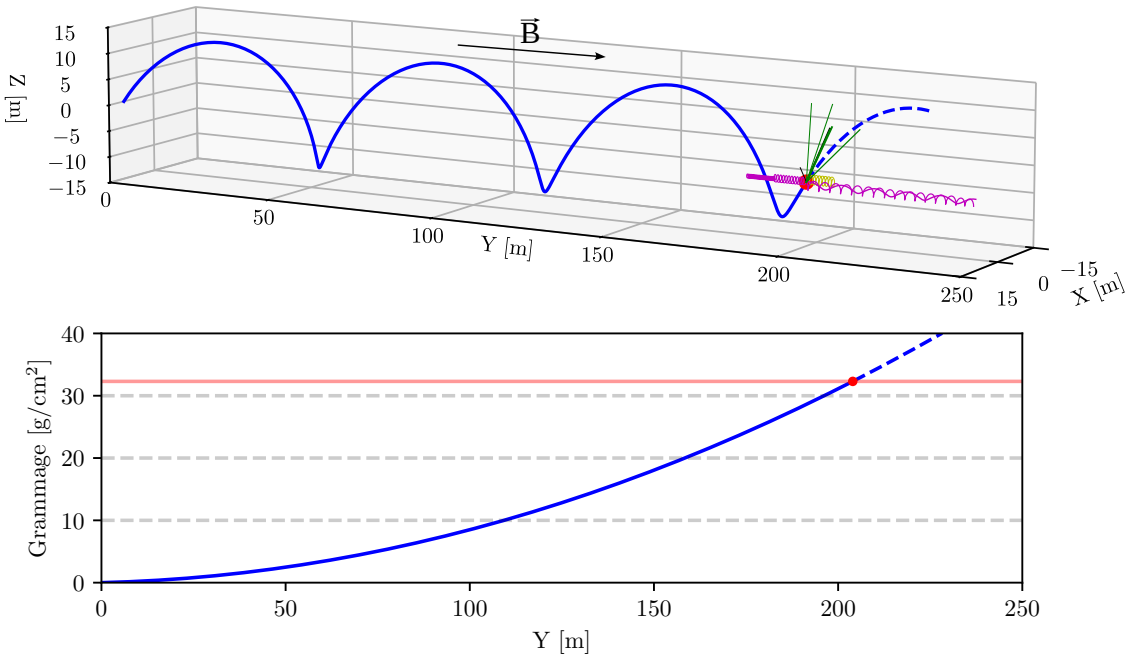
$$X_i = X_{i-1} + \rho_i v_i \Delta t$$





Interaction module

An example of the simulated motion of a 10 GeV proton in a uniform magnetic field. The medium (nitrogen) is set to be non-uniform: $\rho = \rho_0 + ky$, where $\rho_0 = 0.1$ kg/m^3, $k = 0.01$ kg/m^4.

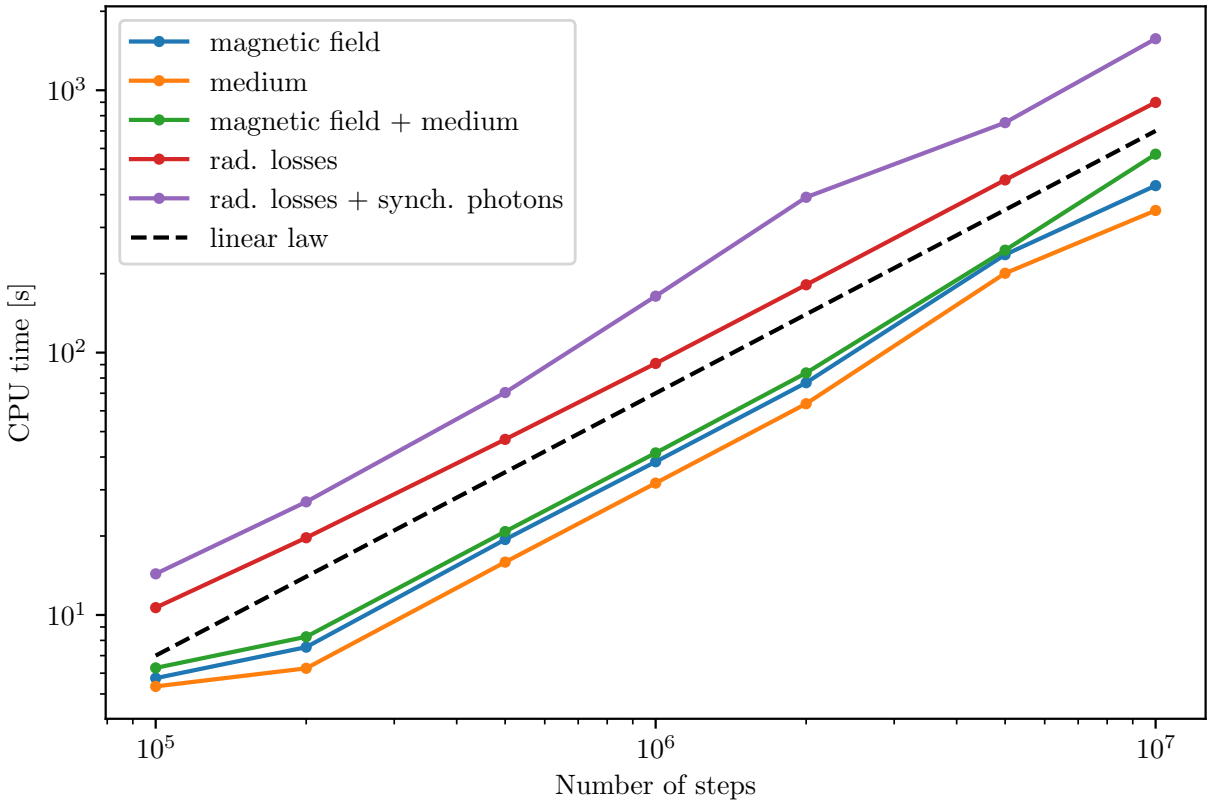


The interaction module computes:

- Energy losses;
- Nuclear interactions;
- Decay of unstable particles;

Performance benchmarks

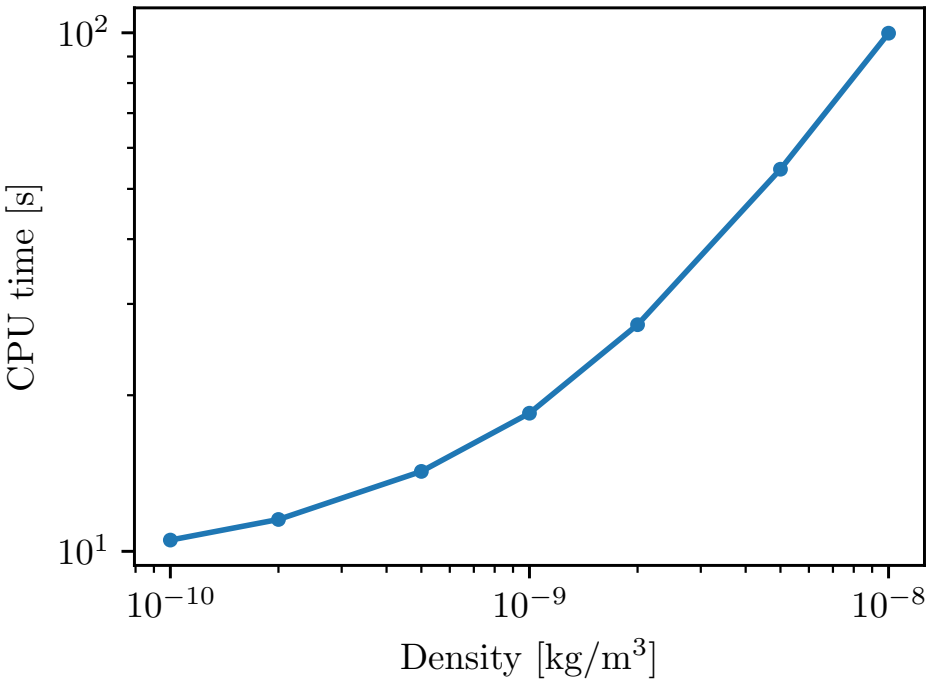
The performance tests were carried out on a 4.70 GHz Ryzen 9 7900X CPU using Python 3.12. The number of trajectory integration steps was varied in different runs to assess the scalability of the computational cost.

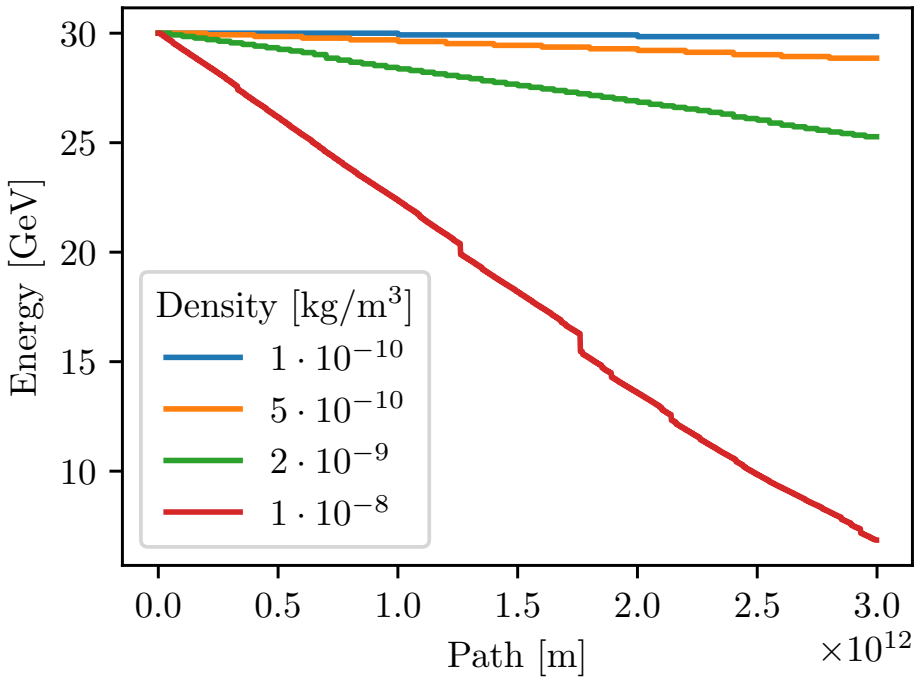


The results show a linear relationship between computation time and the number of integration steps.

Performance benchmarks

The computational cost of simulating a particle's interaction with the medium is primarily influenced by the medium's density. These calculations are triggered when a threshold grammage is reached, leading to more frequent calls to Geant4 subroutines in denser media.





The propagation of a 30 GeV muon through a uniform hydrogen medium over 10^6 integration steps.

Performance benchmarks

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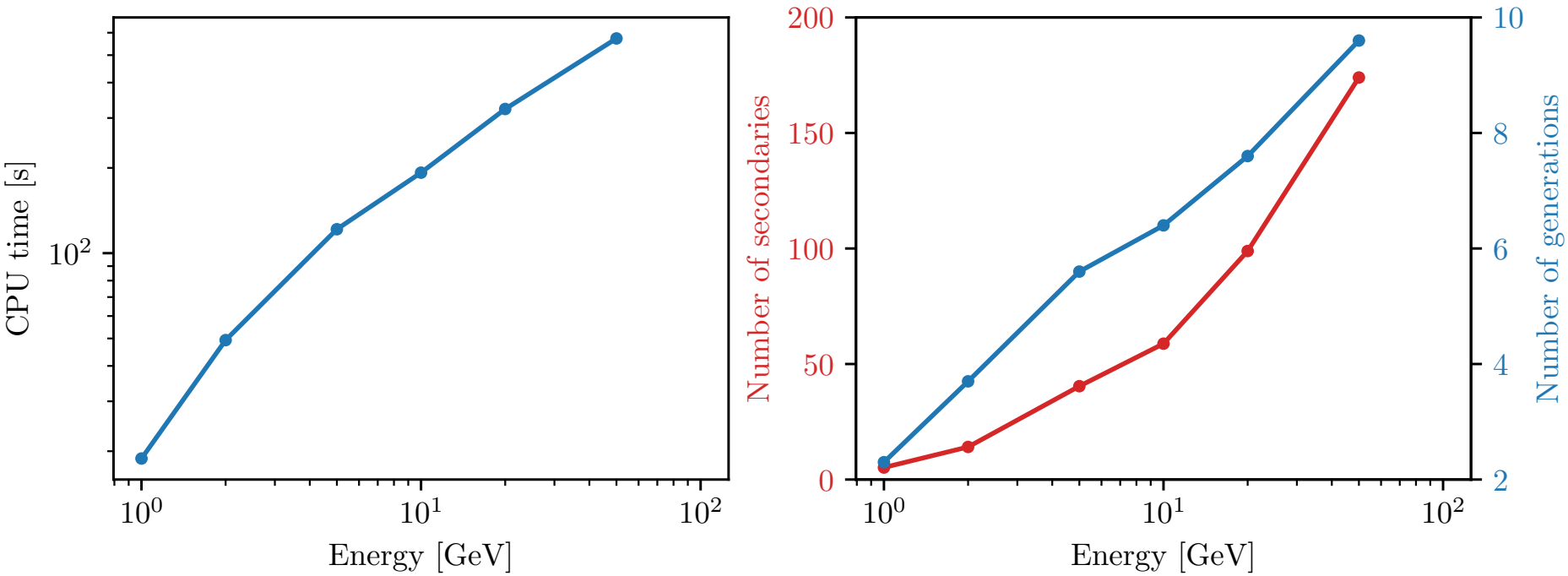
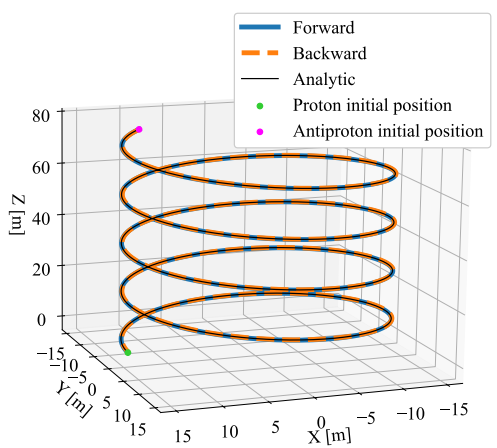


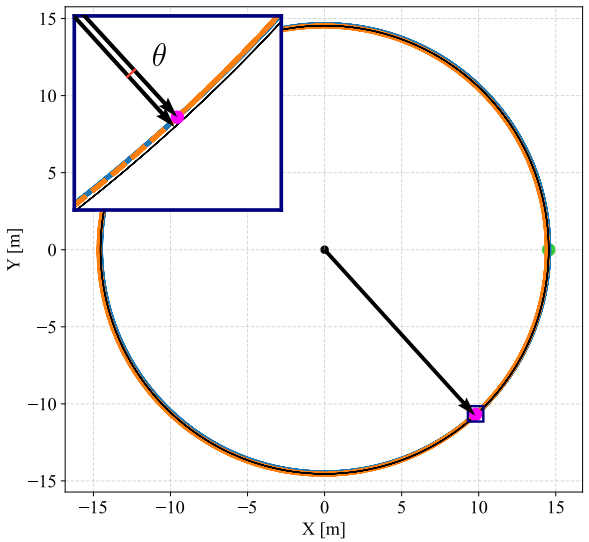
The propagation of proton through a uniform hydrogen medium with density 10^{-9} kg / m^3 over 10^6 integration steps.

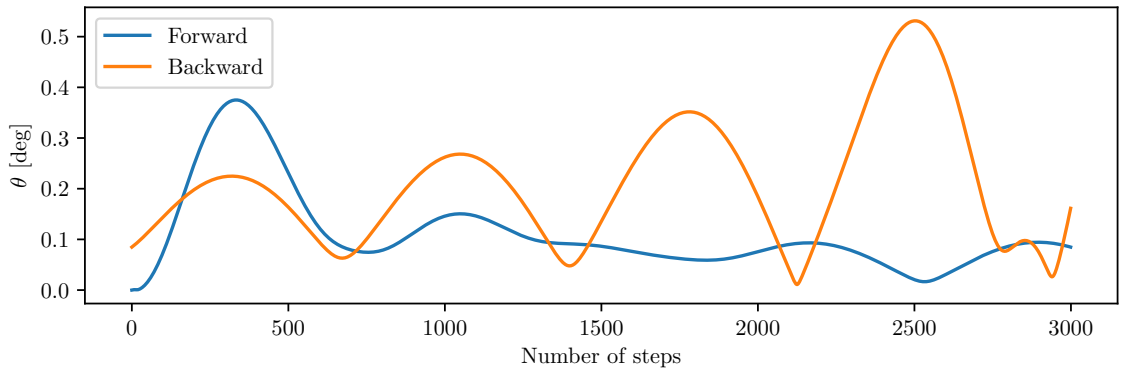
Tracing and backtracing

- A particle with charge q and velocity $\mathbf{v}$ follows a particular trajectory;
- Its corresponding antiparticle with charge $-q$ and velocity $-\mathbf{v}$, when launched from the endpoint of that trajectory, will retrace the path in reverse;

$$\theta = \arccos\left(\frac{\mathbf{r_{num}} \cdot \mathbf{r_{ref}}}{||\mathbf{r_{num}}|| \cdot ||\mathbf{r_{ref}}||}\right)$$

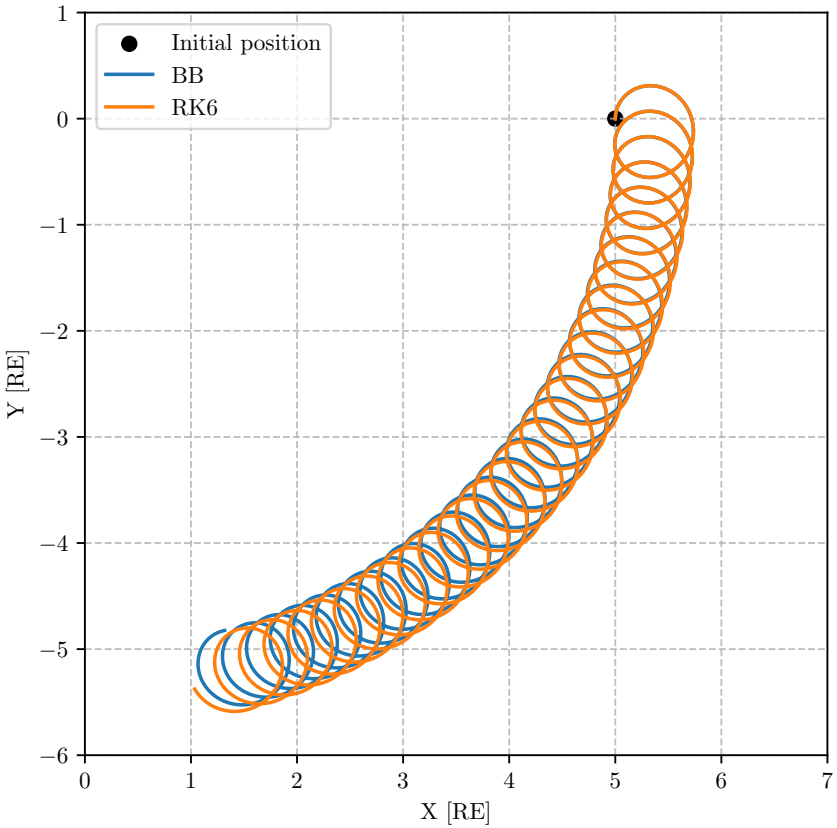


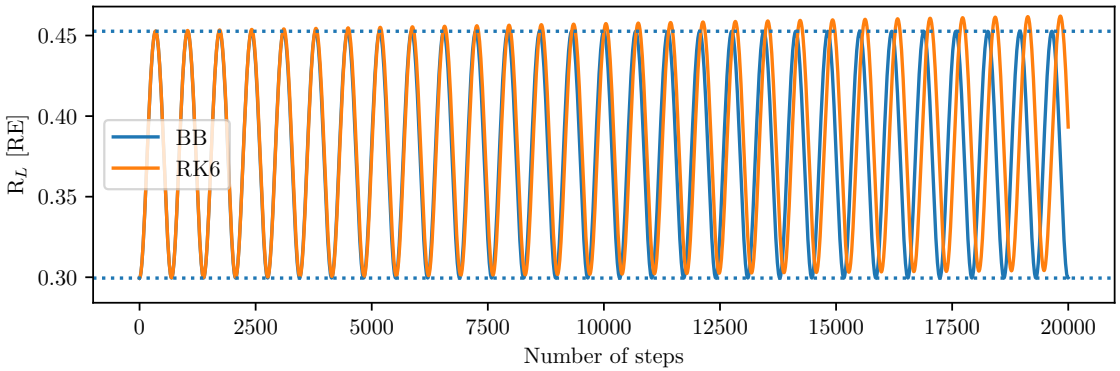




Motion in Earth's dipole magnetic field

A proton with an energy of 10 MeV was initialized at the position (5 RE, 0, 0) with its velocity vector perpendicular to the local magnetic field direction.





The Buneman–Boris integrator offers better long-term accuracy for charged particle motion in magnetic fields.

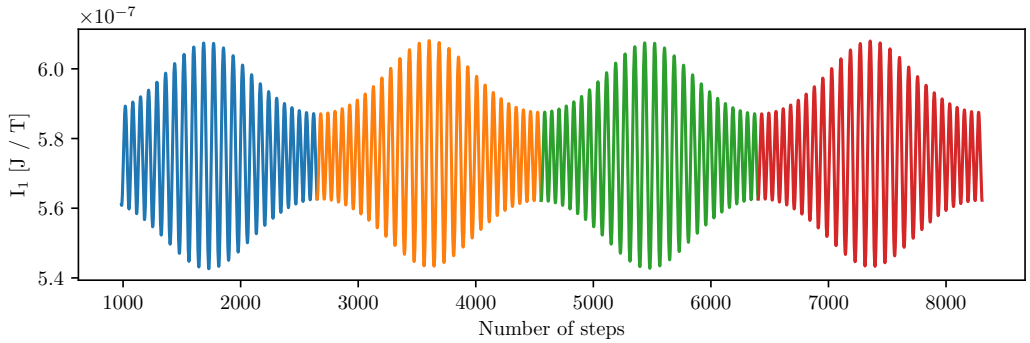
The resulting particle trajectories progressively diverge, highlighting differences in the integration scheme's ability to preserve Larmor motion over extended timescales.

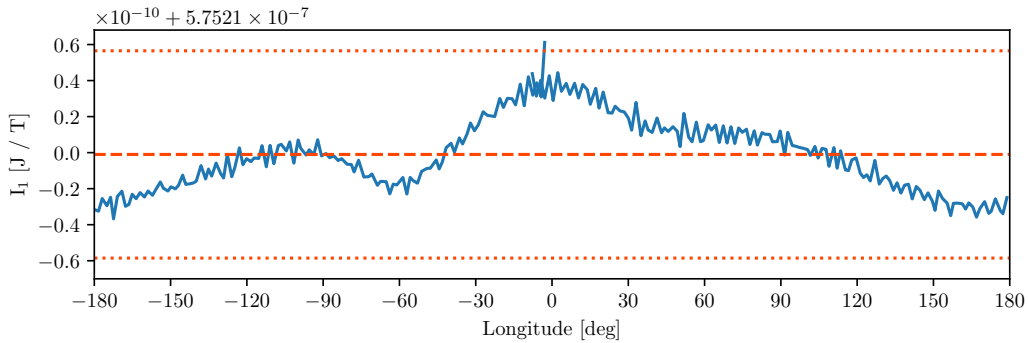
Trappped particles

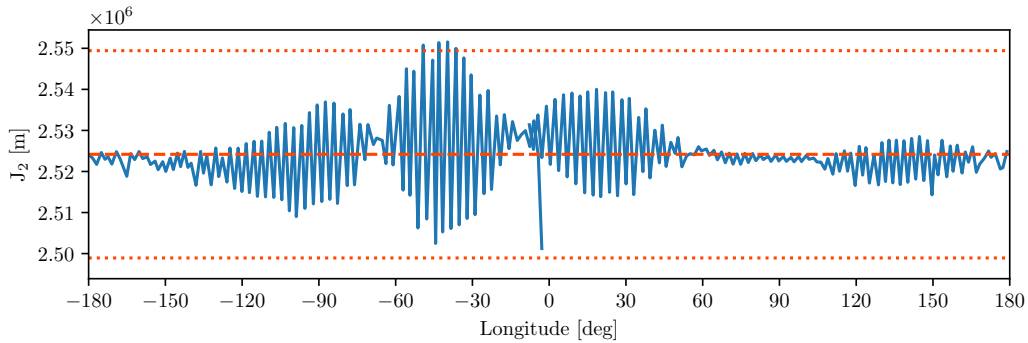
Latitudinal bounce motion and longitudinal drift are characteristic of particles confined in the Earth's radiation belts, where they remain trapped due to the conservation of adiabatic invariants.

- $I_1 = \dfrac{\gamma^2 m v_\perp^2}{2B}$;
- $J_2 = \displaystyle\int_{s_{M_1}}^{s_{M_2}} \sqrt{1 - \frac{B(s)}{B_M}}\, ds$;

We simulated the trajectory of a 40 MeV proton in the Earth's geomagnetic field described by the IGRF model.





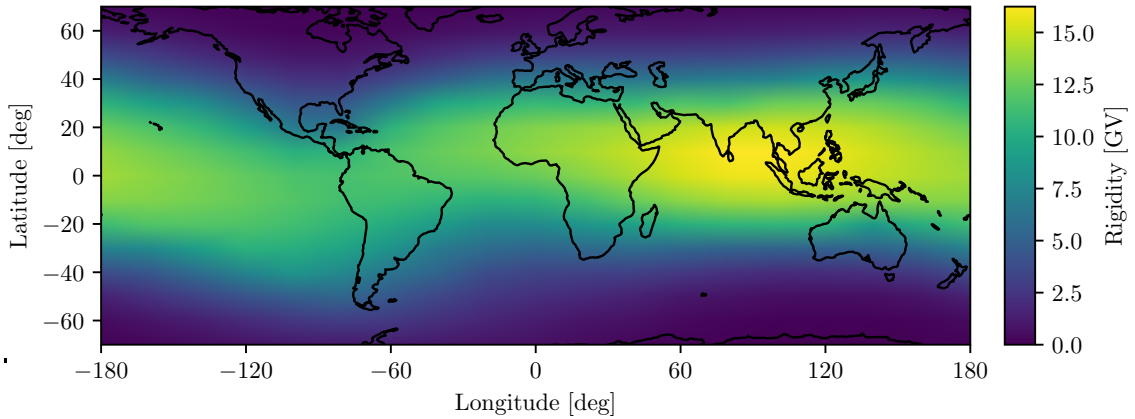


Geomagnetic cutoff

Geomagnetic cutoff rigidity — the minimum rigidity a CR particle can have to reach a given point within the Earth's magnetosphere when penetrating from interplanetary space.
The geomagnetic cutoff rigidity is determined by iteratively backtracing a charged particle. Trajectories are classified as:

- "Allowed" - particles quickly exit the magnetosphere;
- "Forbidden" - particles intersect Earth's surface or become trapped;

We present the geomagnetic cutoff rigidity map using IGRF-14 magnetic field. The calculation was performed at an altitude of 400 km, corresponding to the altitude of low-orbit satellites, 2025.



Adiabatic losses in the heliosphere

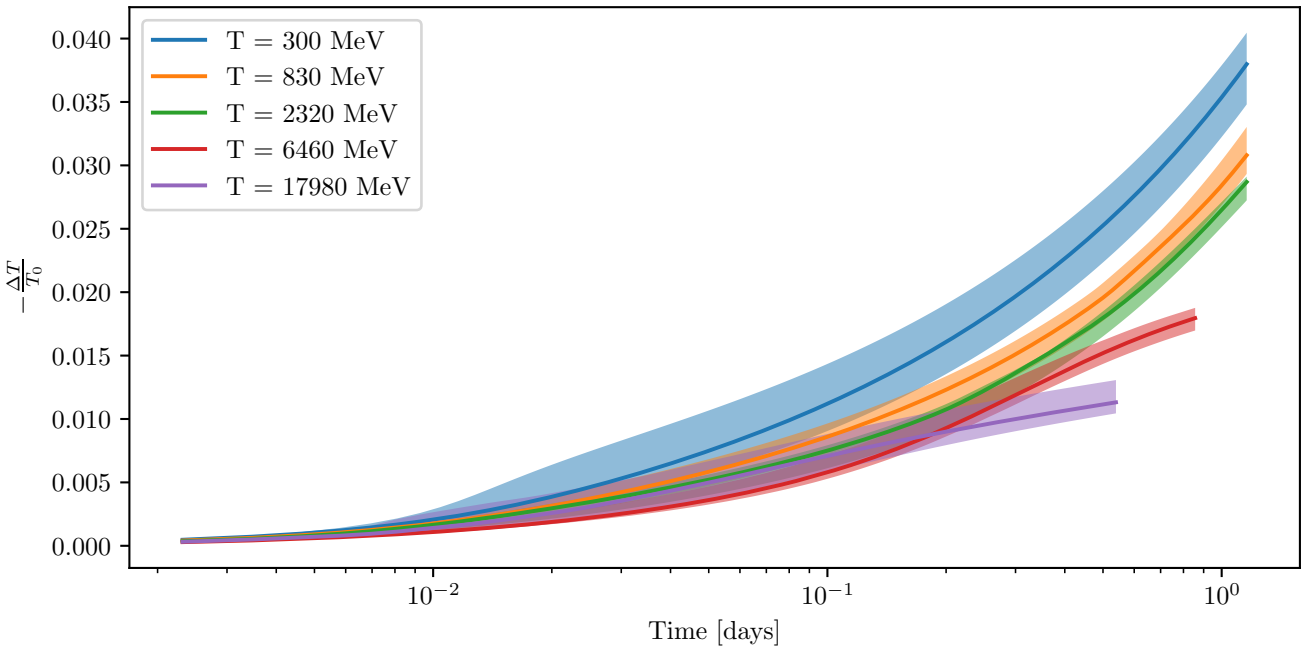
According to Parker, the rate of adiabatic energy loss in the heliosphere can be expressed as:

$$\frac{1}{p}\frac{dp}{dt} = -\frac{1}{3}\nabla \mathbf{V}$$

For a radial solar wind velocity $\nabla \mathbf{V} = 2V/r$, and the rate of energy loss is:

$$\frac{1}{T}\frac{dT}{dt} = -\frac{2}{3}\frac{T+2m}{T+m}\frac{V}{r} \Longrightarrow T_{i+1} = T_i - T_i \cdot \frac{2}{3}\frac{T_i+2m}{T_i+m}\frac{V(r_i)}{r_i}\Delta t;$$

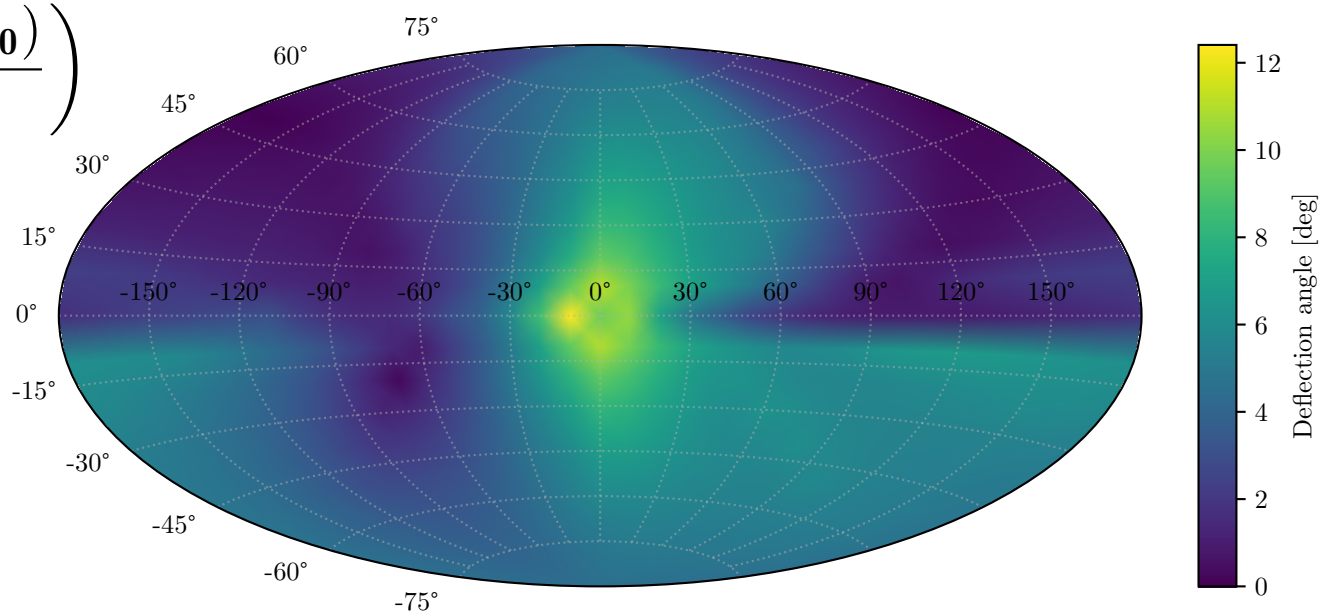
Proton propagation with various initial energies from 1 AU to the boundary of the heliosphere in the regular Parker magnetic field



UHECR deflection in Galaxy

The deflection of ultra-high-energy cosmic rays (UHECR) with energies exceeding 10^{18} eV in Galactic and extragalactic magnetic fields has become a well-established topic in astroparticle physics.
We simulated the backward propagation of 60 EeV antiprotons initiated near the solar system at galactocentric coordinates (−8.5, 0, 0) kpc with a homogeneous isotropic velocity distribution, assuming negligible diffusion at the considered energies.

$$\alpha = \arccos\left(\frac{\mathbf{v_0}\cdot(\mathbf{r_f}-\mathbf{r_0})}{|\mathbf{r_f}-\mathbf{r_0}|}\right)$$

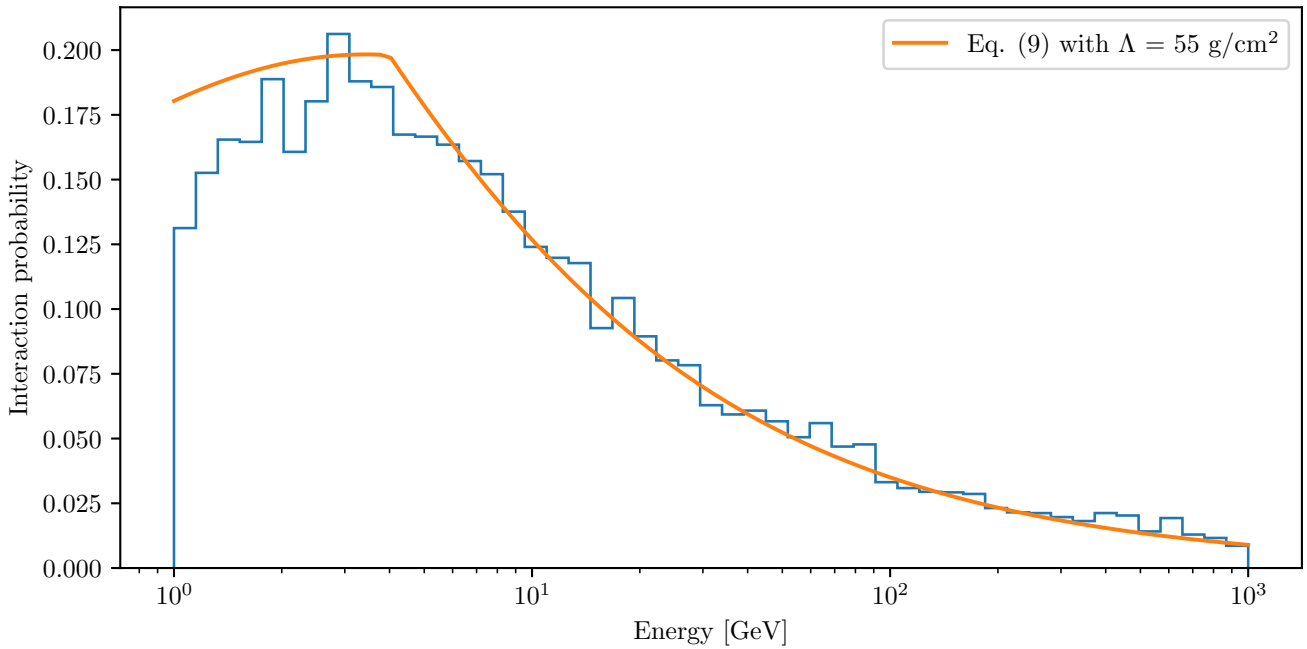


Interaction probability

The likelihood of production of secondary particles due to nuclear interactions with the medium is governed by an exponential law, commonly expressed in terms of the nuclear interaction length Λ (50 - 100 g/cm^2):

$$P_{int} = 1 - \exp\left(-\frac{X}{\Lambda}\right), X - \text{grammage (g/cm}^2\text{) traversed by the particle}$$

We modeled 10^5 protons with a log-uniform energy distribution from 1 GeV to 1 TeV in a homogeneous medium $n_{ISM} = 1cm^{-3}$ with $X(E)$ reported by Simon et al., ApJ (1998).



Conclusion

- The equations of motion are integrated directly, accompanying physical processes are optionally taken into account;
- A wide range of built-in models available out-of-the-box;
- Modular architecture enables users to modify or define from scratch various modeling components;
- The package reproduces various physical effects and phenomena;
- This approach offers an alternative way of modelling cosmic-ray physics;

Thank you for your attention!

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For details and source code