# Production and Attenuation of Cosmic-Ray Boosted Dark Matter

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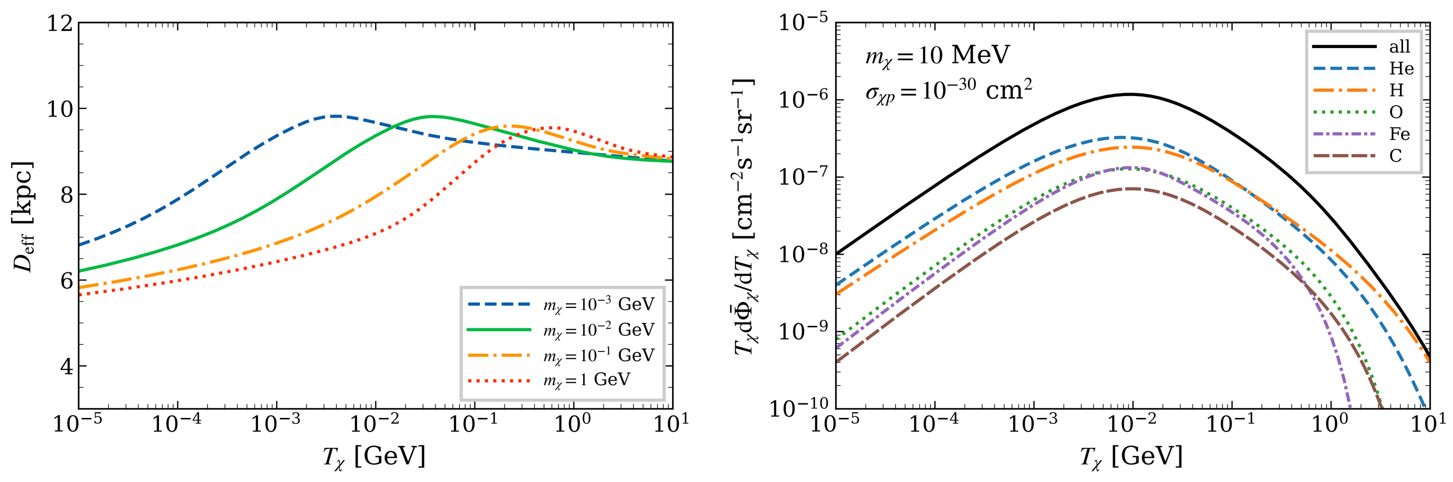
## Introduction

Cosmic rays (CRs) are high-energy charged particles that diffuse throughout the Galaxy. If dark matter (DM) particles can scatter off the nuclei in the detectors of direct detection experiments, they can also be up-scattered by cosmic rays in the space. This small amount of cosmic-ray boosted DM (CRDM) exhibits high energy, making it detectable even if the DM mass is far below 1 GeV. Following this idea we performed a refined analysis on the production and attenuation of CRDM. For the production process, we determined the parameter of the effective distance $D_{\rm eff}$ for CRDM production using spatial-dependent CR fluxes and including the contributions from the major heavy CR nuclear species. Regarding the Earth attenuation process, we compared analytical approximation and numerical simulation approaches. We found that the presence of the nuclear form factor strongly suppresses the effect of Earth attenuation. To simulate the Earth attenuation, we developed the DarkProp code and are currently working on incorporating the DM-nucleus inelastic scattering within it.

## 1. Production of Cosmic-Ray Boosted Dark Matter

We have made significant improvements by incorporating a fully spatial-dependent cosmic ray (CR) distribution within the Galaxy and considering the contributions from major heavy CR nuclear species ($Z \leqslant 28$). The key findings resulting from these enhancements are as follows:

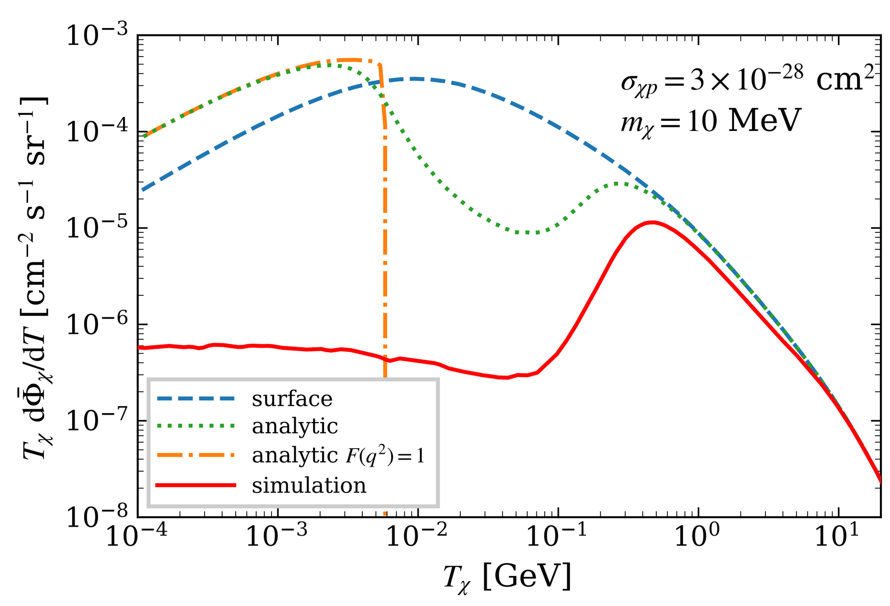
- The effective distance, which characterizes the size of the region where CRDM is produced, is found to be energy-dependent and varies within a range of approximately 6-10 kpc. This determination is based on the CR distribution modeled by GALPROP.
- Our analysis reveals that heavy cosmic-ray nuclei contribute significantly to the CRDM flux, comparable to that produced by light nuclei such as protons and helium.




## 2. Earth Attenuation Effect

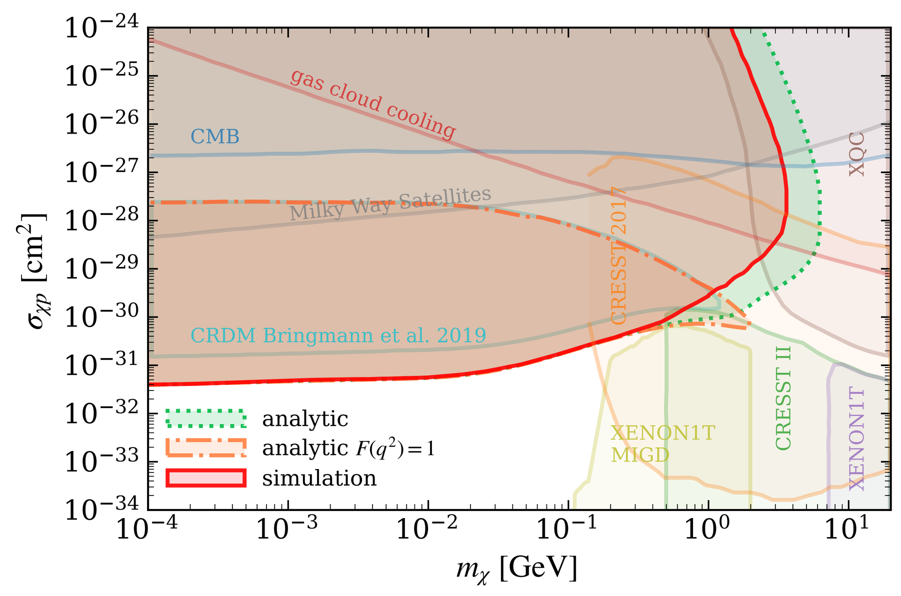
Before reaching underground detectors, DM particles may lose energy due to the elastic scattering with the nuclei inside the Earth. This phenomenon is known as the Earth attenuation effect. We compared analytic approximation and numerical simulation approaches for calculating this effect. Our findings are as follows:

- Simulation results show a stronger attenuation compared to the analytic approximation.
- The presence of the nuclear form factor suppresses the attenuation at high energy.




## 3. New Exclusion Regions

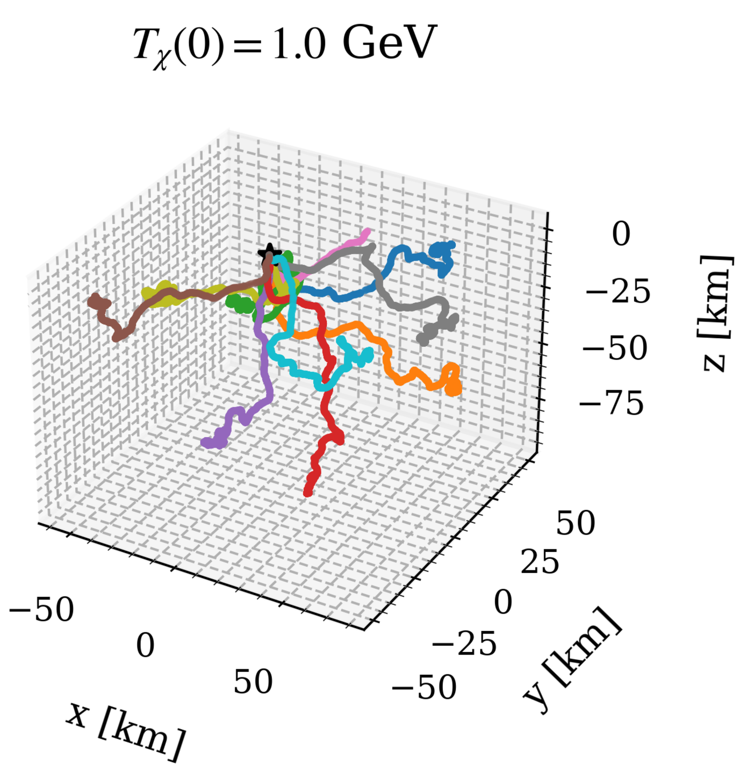
Using updated CRDM flux and data from the XENON1T experiment, we pushes the exclusion lower bounds on the DM-nucleus spin-independent cross section down to $\sigma_{\chi p} \sim 4 \times 10^{-32}$ cm$^2$ for DM particle mass at MeV scale and below. Due to the nuclear form factor, the cross section that can be excluded by the XENON1T data can be a few orders of magnitude higher, which closes the gap in the cross sections excluded by the XENON1T experiment and that by the astrophysical measurements such that for the cosmic microwave background (CMB), galactic gas cloud cooling, and structure formation, etc.




## 3. DarkProp: The Monte Carlo Simulation Code

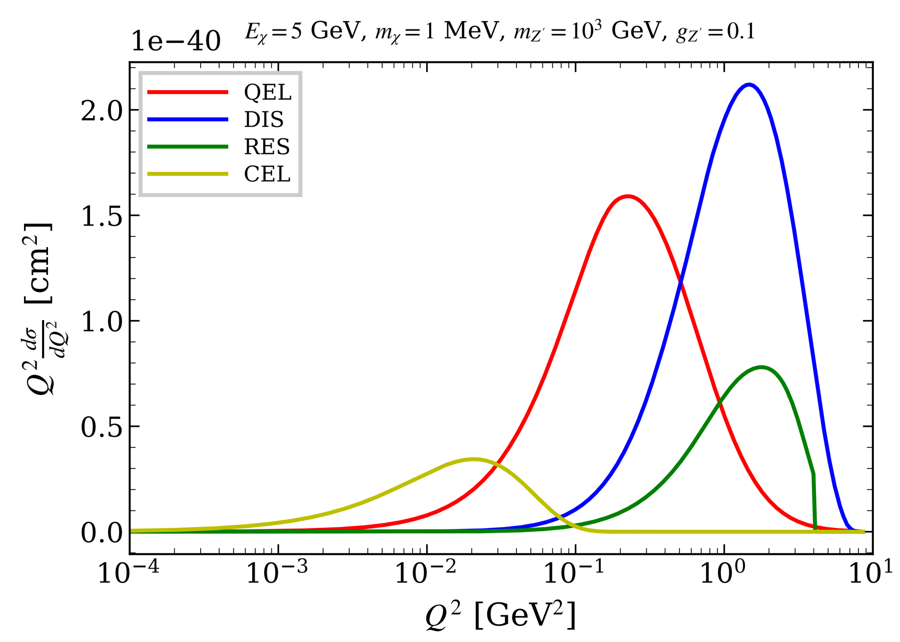
We developed the `DarkProp` code for simulating dark matter propagation within the Earth (`http://yfzhou.itp.ac.cn/darkprop`).
Key features of the code include:

- User-friendly: provides an executable, a C++ library, and a Python binding
- High performance: optimized memory usage and parallelized using MPI
- Flexibility: supports both relativistic and non-relativistic kinematics
- Extensibility: modular design for changing DM and Earth models




## 4. Ongoing Work: Inelastic Scattering

Due to the possibility of DM particles being accelerated to high energies exceeding 1 GeV, inelastic scattering between DM and nuclei can occur. These scattering processes involve the ejection of nucleons from nuclei (quasi elastic scattering, QEL), excitation of nucleon to hadronic resonances (resonance scattering, RES), and fragmentation into a hadronic shower (deep inelastic scattering, DIS). These inelastic processes significantly contribute to the total cross section at high energy and influence the Earth attenuation effect experienced by DM particles. As part of our work, we are currently incorporating these inelastic processes into our simulation of Earth attenuation.




## Reference

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