An Analytic Approach to Light Dark Matter Propagation

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GUINEAPIG 2023, Montreal
July 13, 2023

Arthur B. McDonald
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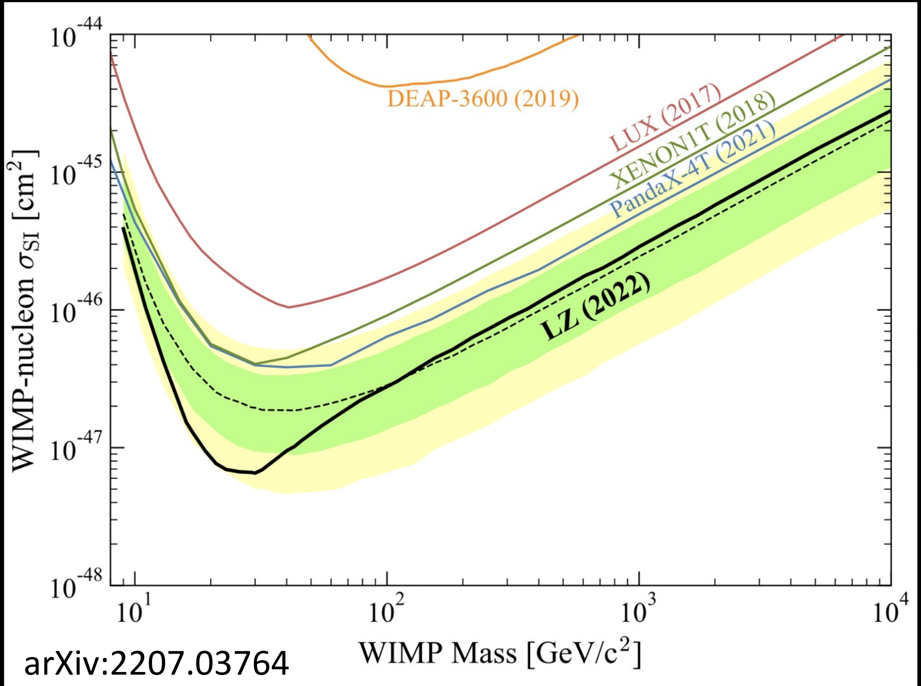
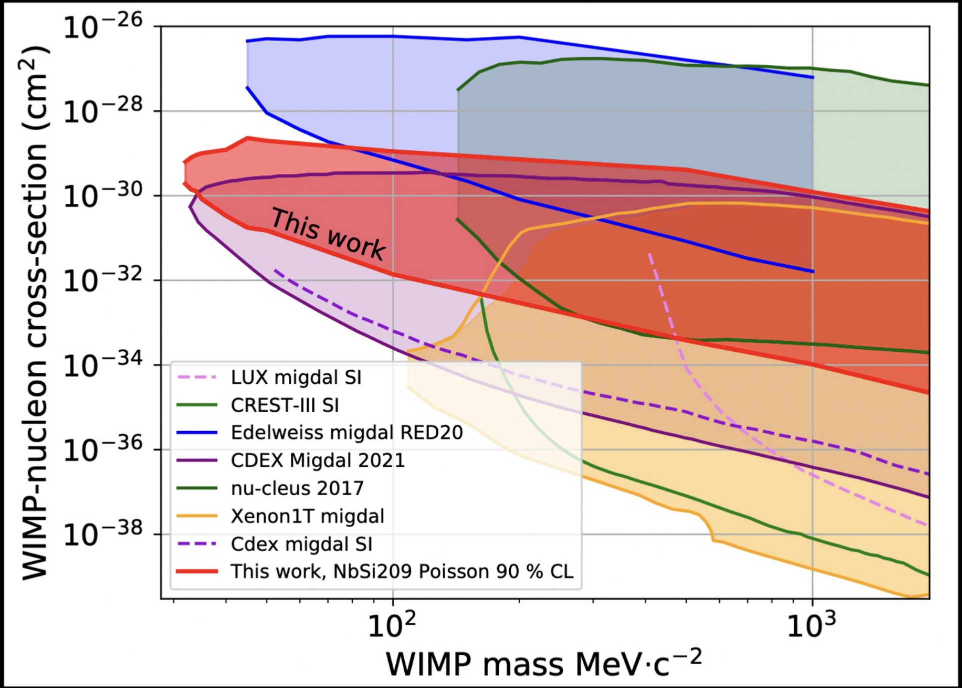
An Intro to Dark Matter Attenuation

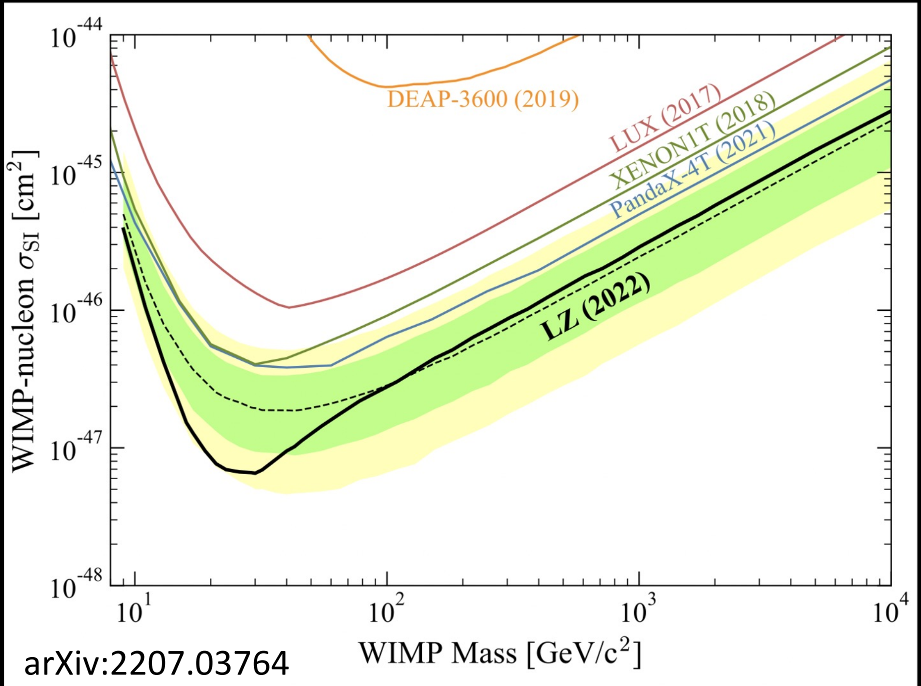
Direct Detection Limits



Direct Detection Limits



arXiv:2203.03993 (Edelweiss)



Attenuation: Straight Line Approximation

PHYSICAL REVIEW D VOLUME 41, NUMBER 12 15 JUNE 1990

Opening the window on strongly interacting dark matter

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Institute for Advanced Study, Princeton, New Jersey 08540

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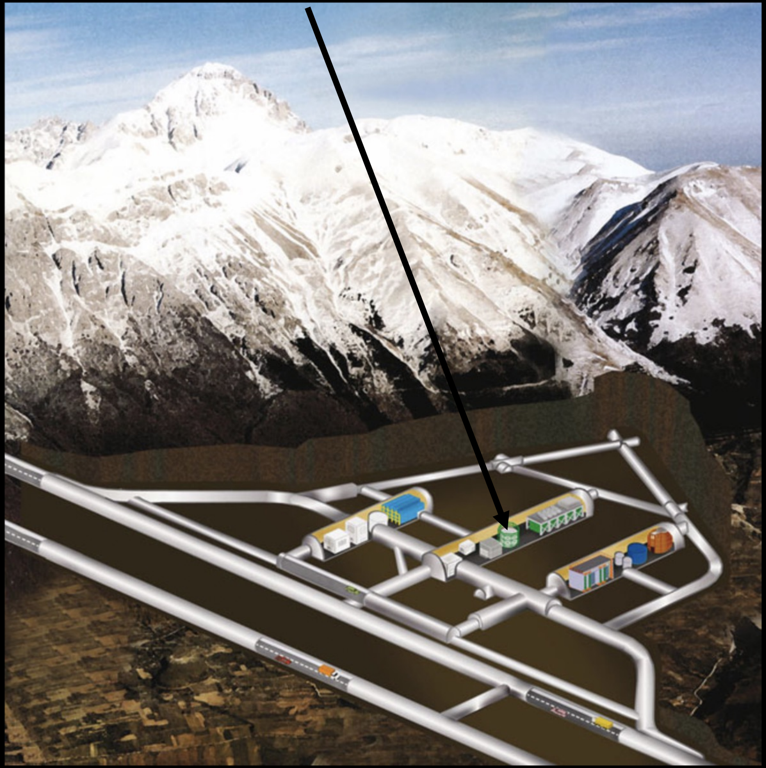
Center for Particle Astrophysics, University of California, Berkeley, California 94720

Savas Dimopoulos*
CERN TH-Division, 1211 Geneva 23, Switzerland

(Received 2 February 1990)

We discuss the possibility that the dark matter consists of strongly interacting massive particles (SIMP's) which have cross sections with ordinary matter which are larger than characteristic weak-interaction cross sections. We show that, while results from $\beta\beta$ decay, cosmic-ray detectors, galactic-halo stability, the cooling of molecular clouds, proton-decay detectors, and the existence of old neutron stars and the Earth constrain the interactions of the missing matter with ordinary matter over a broad range of parameter space, there still exist several windows for SIMP's. It is noteworthy that there are two regions of less than geometric cross sections: one with masses of 10^5-10^7 GeV and another with masses above 10^{10} GeV.

Attenuation: Straight Line Approximation



Assume that dark matter follows a straight (ballistic) trajectory, every particle losing the average possible amount of energy:

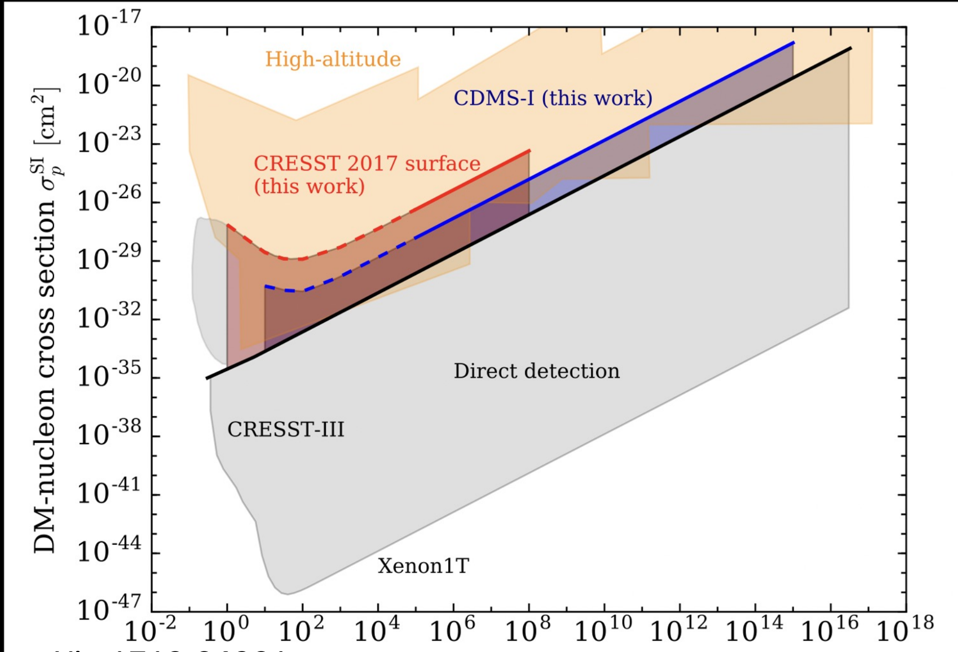
$$\frac{\mathrm{d}\langle E_\chi \rangle}{\mathrm{d}t} = -\sum_i n_i(\mathbf{r})\,\langle E_R \rangle_i\,\sigma_i(v)\,v\,,$$

- n_i : number density of nuclei in overburden
- $\langle E_R \rangle_i$: average recoil energy
- σ_i : DM-nucleus cross section

Left: Schematic of LNGS

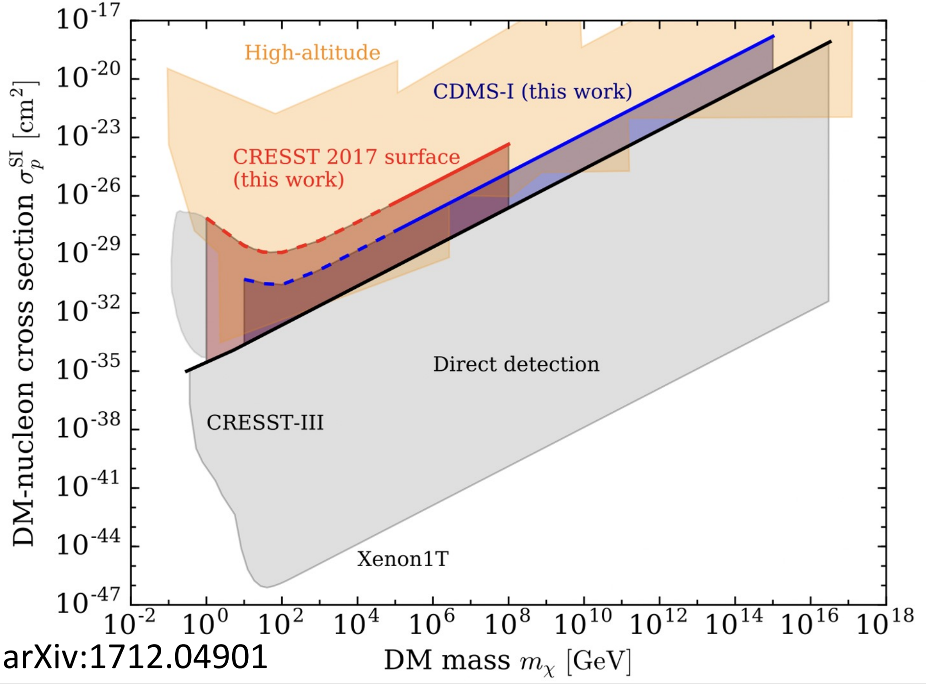
-Credit: https://www.appec.org

Attenuation: Straight Line Approximation



arXiv:1712.04901

Attenuation: Straight Line Approximation



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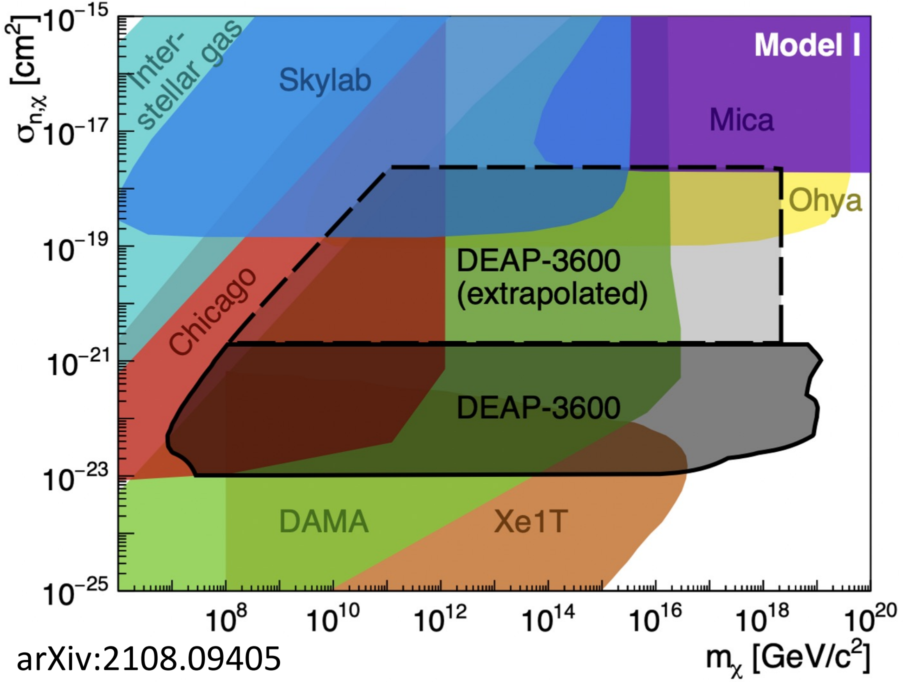
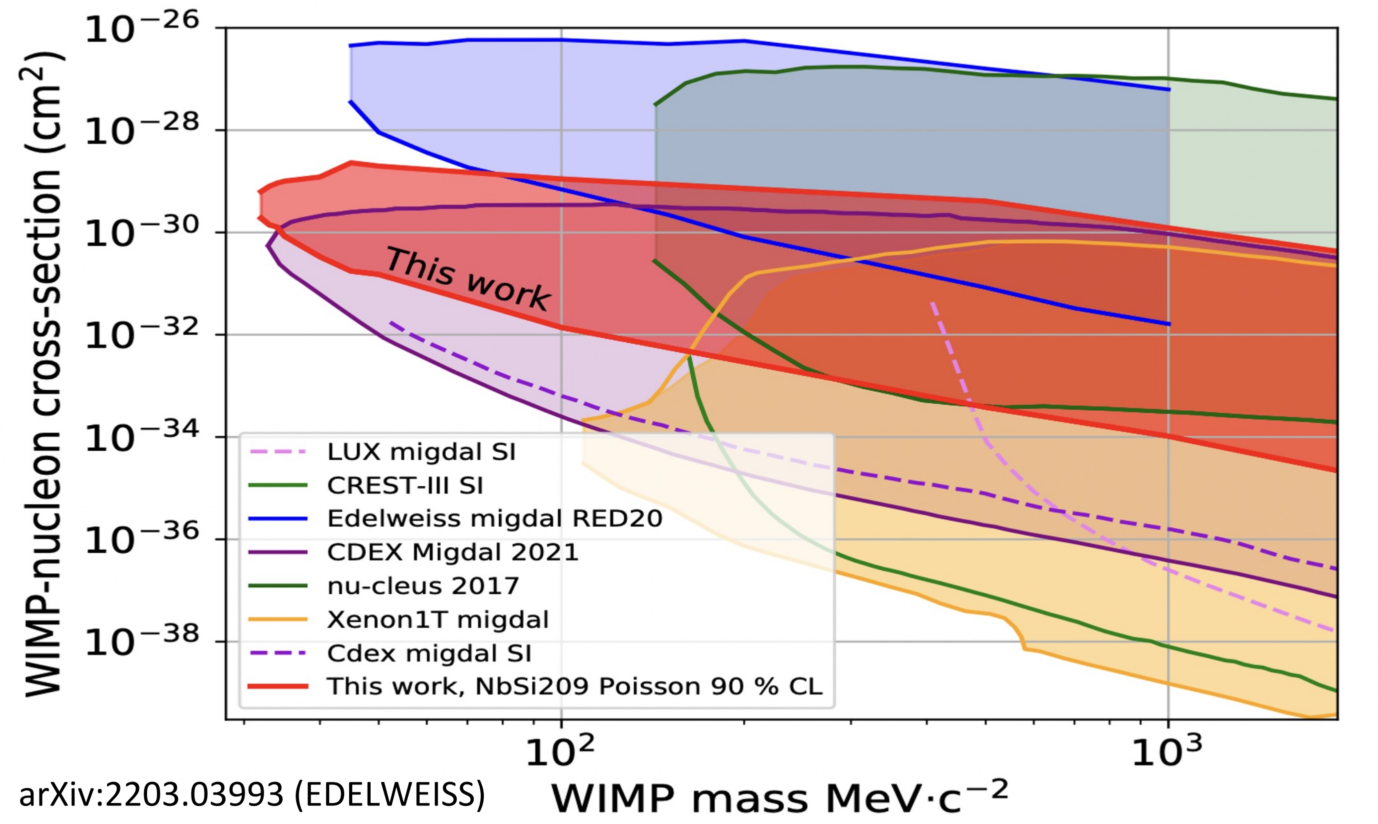


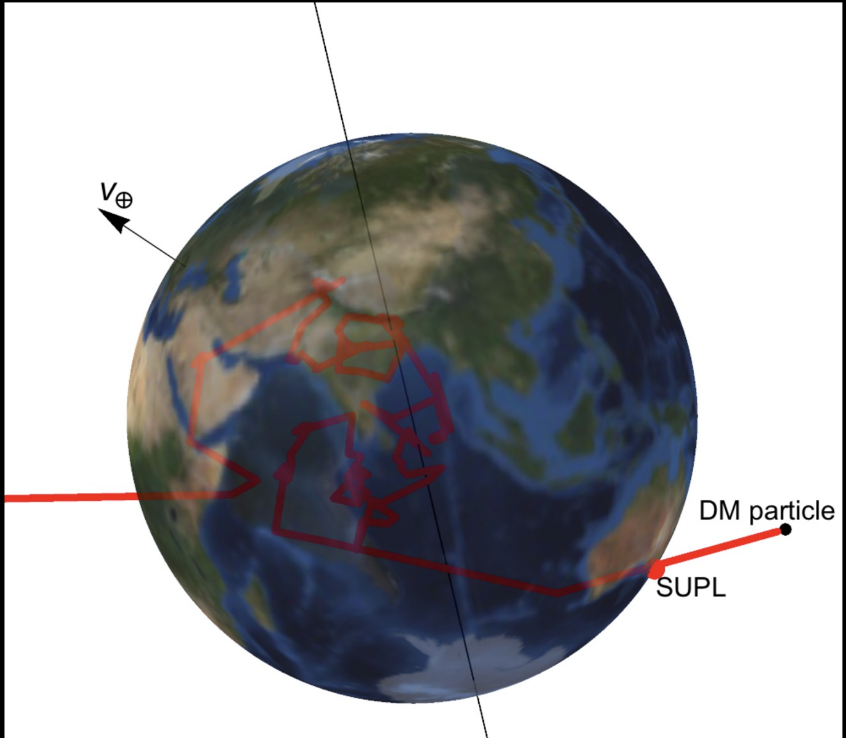
arXiv:2108.09405

Attenuation: Straight Line Approximation



arXiv:2203.03993 (EDELWEISS)

Attenuation: Monte Carlo Simulations

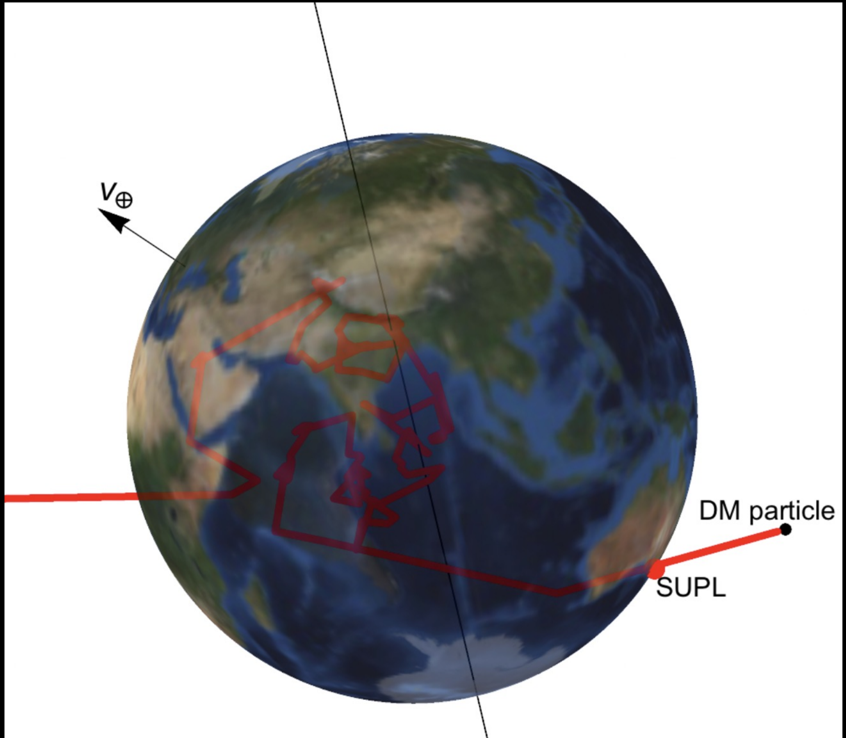


timonemken.com/code, arXiv:1706.02249

Alternative approach: numerically simulate millions of dark matter particles scattering in Earth

- Initialize a particle above the Earth with initial velocity **v**
- Choose distance particle travels without scattering from exponential path length distribution
- Choose target + scattering angle, update velocity
- Stop if particle is detected, loses too much energy, or leaves Earth

Attenuation: Monte Carlo Simulations



timonemken.com/code, arXiv:1706.02249

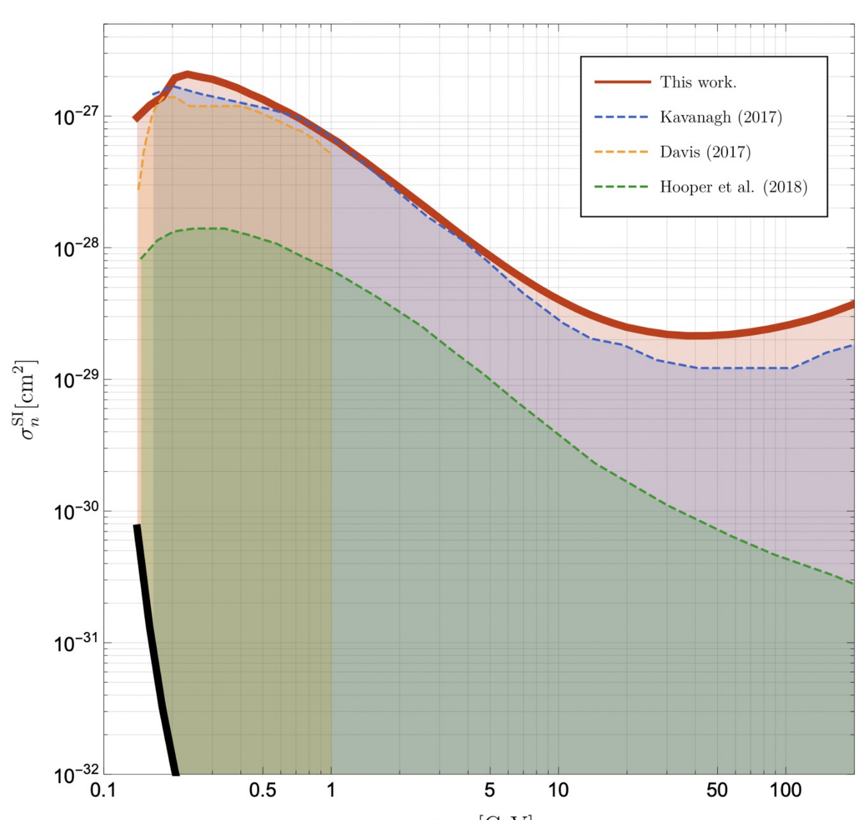
Examples:

- DaMaSCUS: Dark Matter Simulation Code for Underground Scatterings, Timon Emken
- DMATIS: Dark Matter Attenuation Importance Sampling, M. Shafi Mahdawi
- DarkProp (for cosmic ray boosted dark matter), Chen Xia

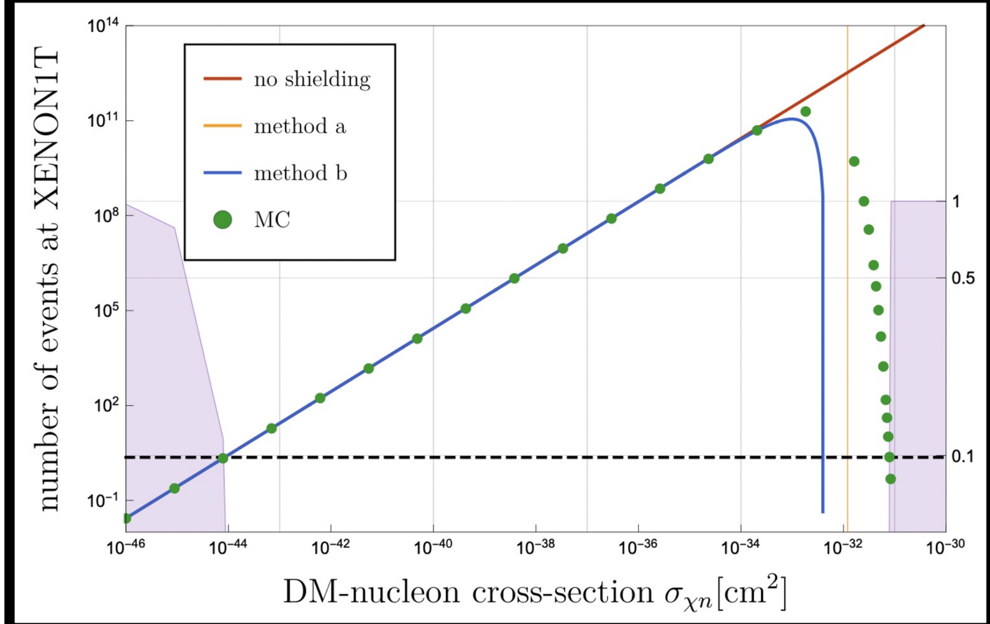
See also:

CVC and Beacom: PRD 100, 103011 (2019)
PROSPECT Collaboration, **CVC**: PRD 104, 012009 (2021)

Straight Line vs. Monte Carlo



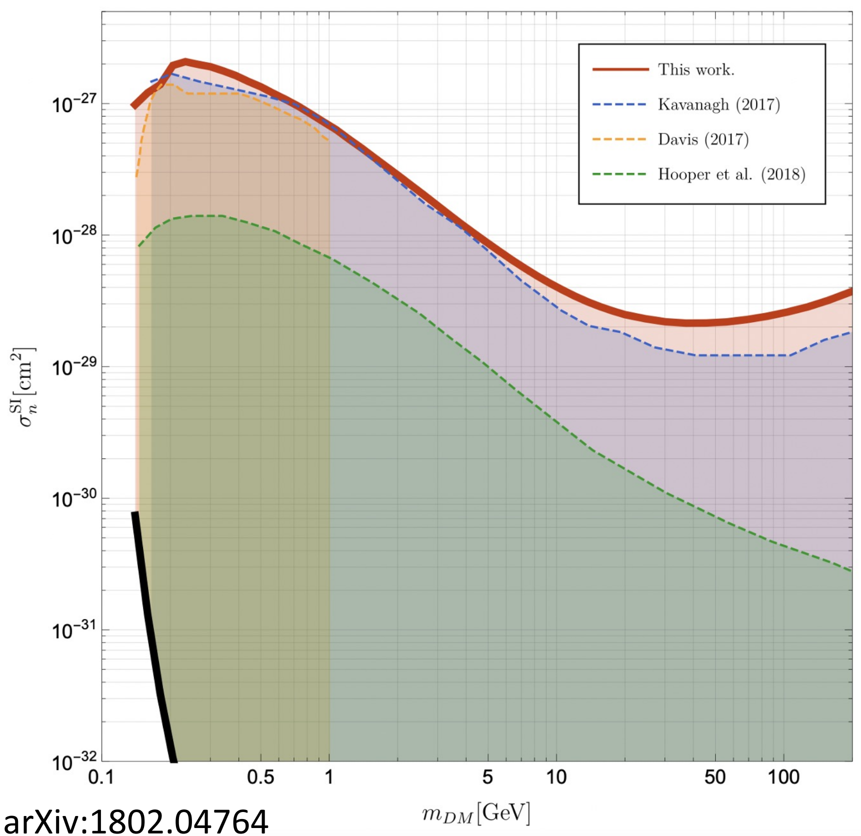
arXiv:1802.04764



MC: Monte Carlo code

Method B: Straight Line Approximation

Straight Line vs. Monte Carlo



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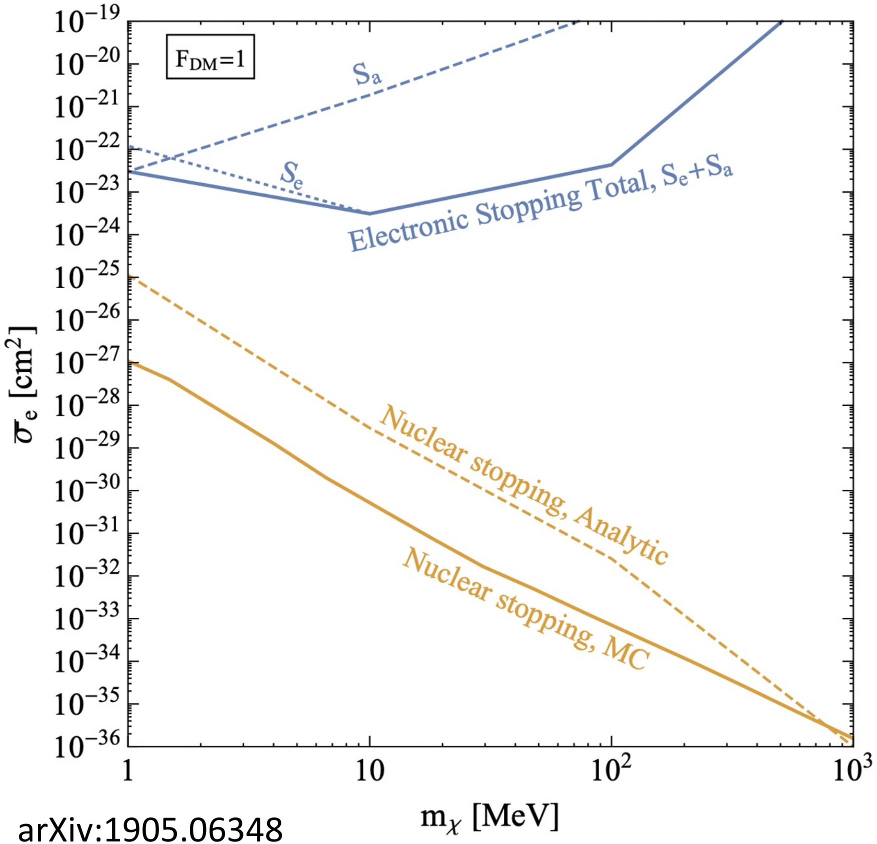
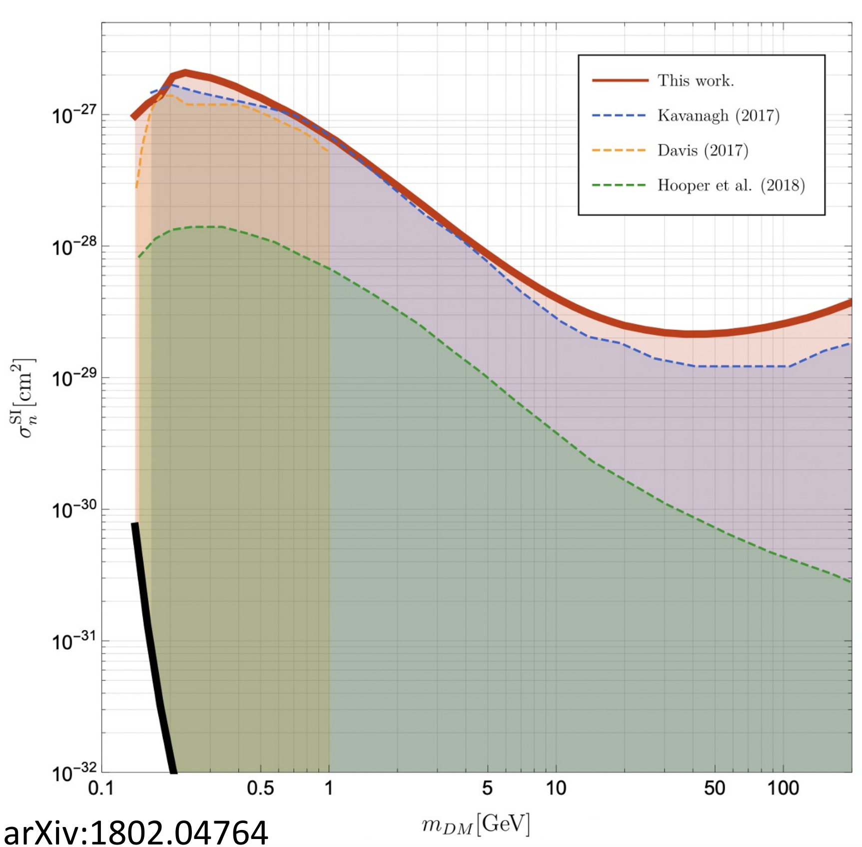


arXiv:1905.06348

A New Analytic Approximation

Based on **CVC**, PRL 130, 221001 (2023)

Probability of Not Scattering



arXiv:1802.04764

We want an alternative to both Monte Carlo and straight-line approaches

Hooper & Mcdermott (Green):

- Compute fraction of dark matter reaching CRESST surface detector without scattering

$$P_{\text{initial}}(x) = \frac{1}{l} e^{-x/l}$$

$$P(z, \theta) = \frac{1}{l \cos(\theta)} e^{-z/(l \cos(\theta))}$$

$$P(z) = \int_0^1 \frac{\mathrm{d}\cos(\theta)}{l \cos(\theta)} e^{-z/(l\cos(\theta))} = \frac{1}{l}\Gamma(0, z/l)$$

What about scattering?

Signatures of Earth-scattering in the direct detection of Dark Matter

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[b]Chalmers University of Technology, Department of Physics,
SE-412 96 Göteborg, Sweden
[c]CP[3]-Origins, University of Southern Denmark,
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Abstract. Direct detection experiments search for the interactions of Dark Matter (DM) particles with nuclei in terrestrial detectors. But if these interactions are sufficiently strong, DM particles may scatter in the Earth, affecting their distribution in the lab. We present a new analytic calculation of this 'Earth-scattering' effect in the regime where DM particles scatter at most once before reaching the detector. We perform the calculation self-consistently, taking into account not only those particles which are scattered away from the detector, but also those particles which are deflected towards the detector. Taking into account a realistic model of the Earth and allowing for a range of DM-nucleon interactions, we present the EARTHSHADOW code, which we make publicly available, for calculating the DM velocity distribution after Earth-scattering. Focusing on low-mass DM, we find that Earth-scattering reduces the direct detection rate at certain detector locations while increasing the rate in others. The Earth's rotation induces a daily modulation in the rate, which we find to be highly sensitive to the detector latitude and to the form of the DM-nucleon interaction. These distinctive signatures would allow us to unambiguously detect DM and perhaps even identify its interactions in regions of the parameter space within the reach of current and future experiments.

JCAP01(2017)012

What about scattering?

$$P_0(z) = \frac{1}{l}\Gamma(0, z/l)$$

$$P_1(z) = \int P_0(z')P(z-z')dz'$$

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Assume isotropic scattering (heavy mediator)

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$$P_n(z) = \int_0^\infty P_{n-1}(z')\frac{1}{2l}\Gamma(0, |z-z'|/l)dz'$$

This process is iterative!
Can compute probabilities through n scatterings

Energy Loss

$$P(\Delta E) = \frac{\sum_A \frac{n_A \sigma_{\chi A}}{E_{max,A}} \theta(E_{max,A} - \Delta E)}{\sum_A n_A \sigma_{\chi A}}$$

$$\frac{dN}{dE}_n(E) = \int \left(\frac{E}{E - \Delta E} \right) \frac{dN}{dE}_{n-1} \left(\frac{E^2}{E - \Delta E} \right) P(\Delta E) \, d\Delta E$$

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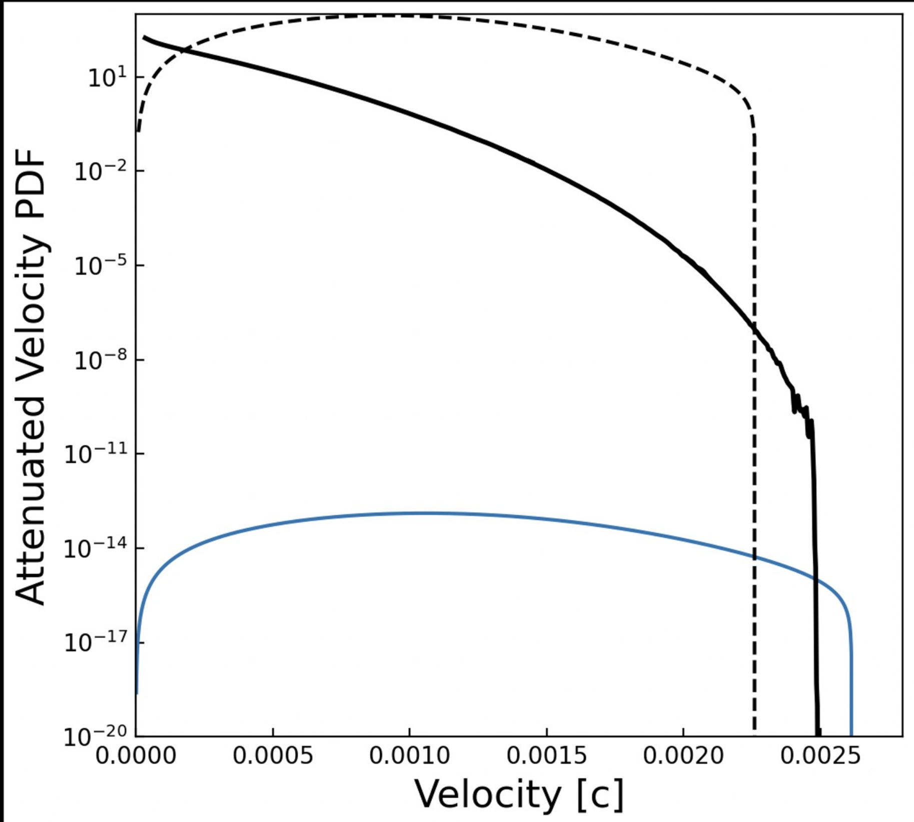
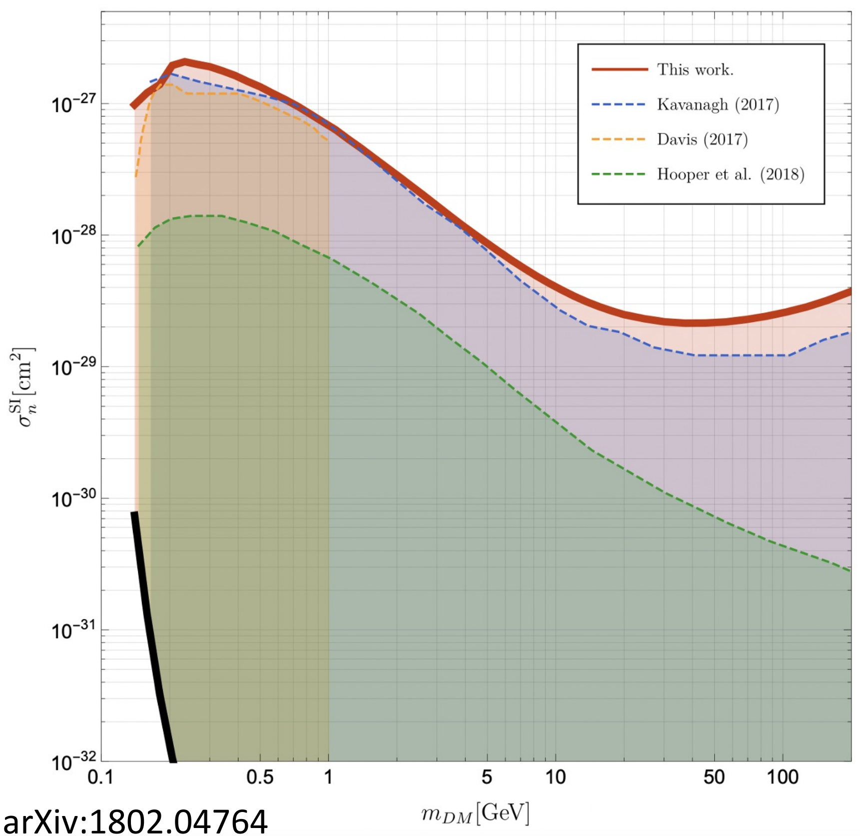
$$\frac{dN}{dE}_{total}(z, E) = \sum_{n=0}^{\infty} \int_z^{\infty} P_n(z') dz' \frac{dN}{dE}_n(E)$$

Velocity Distribution



M_X = 100 MeV
σ_{XN} = 5*10^{-30} cm^2
Depth = 1400 m

Probability of Not Scattering



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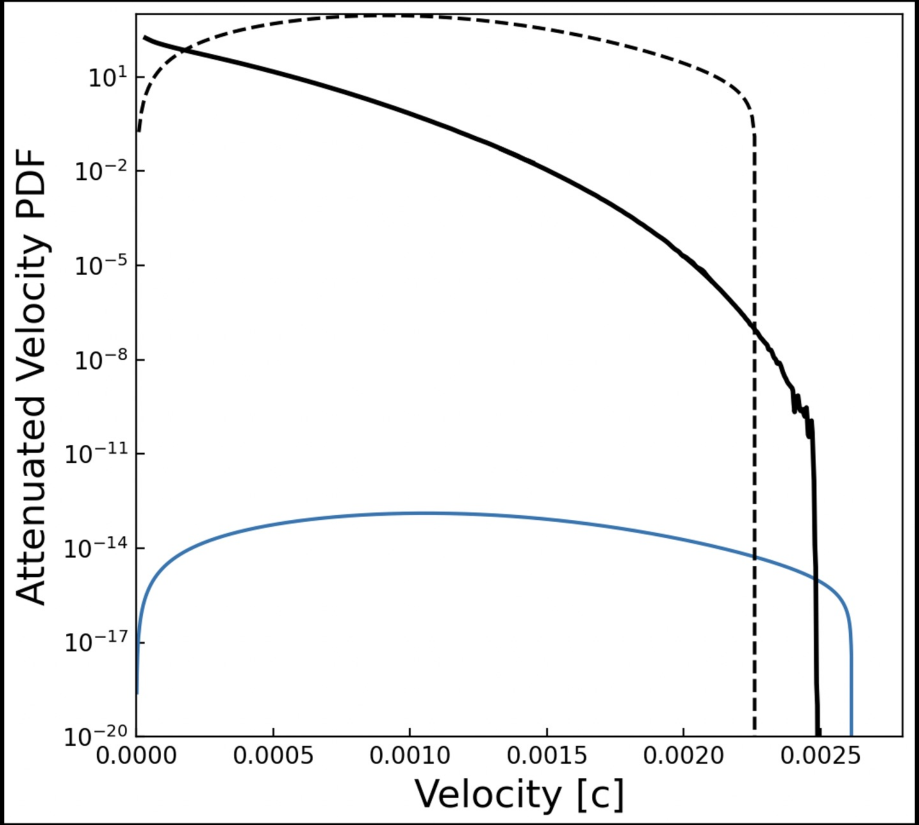

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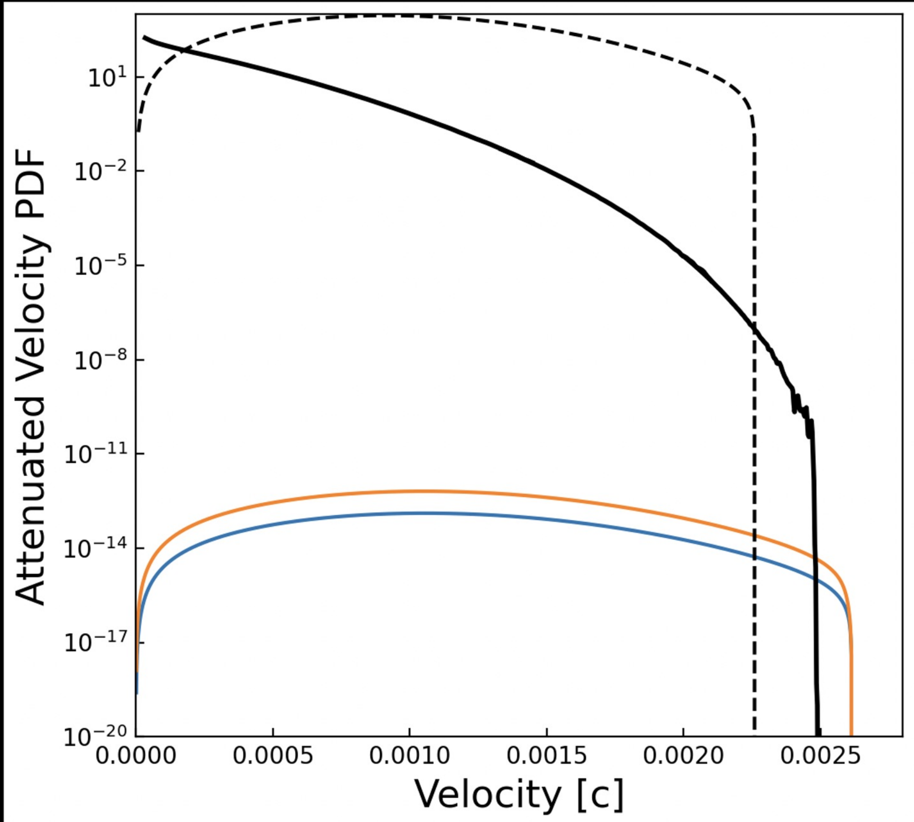

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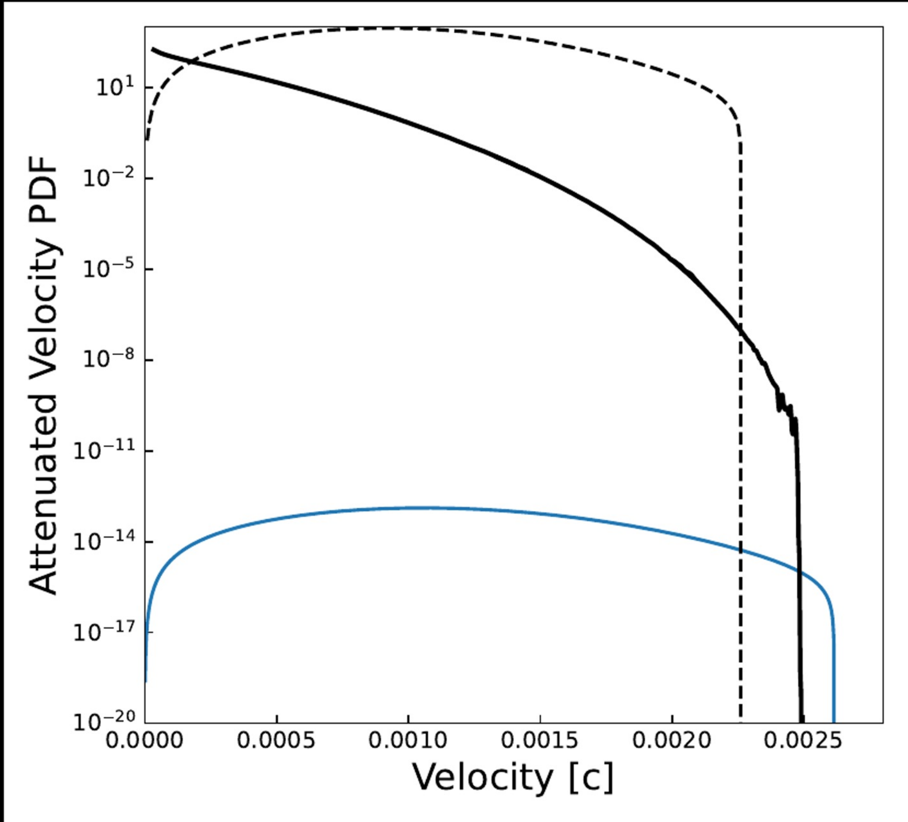

M_X = 100 MeV
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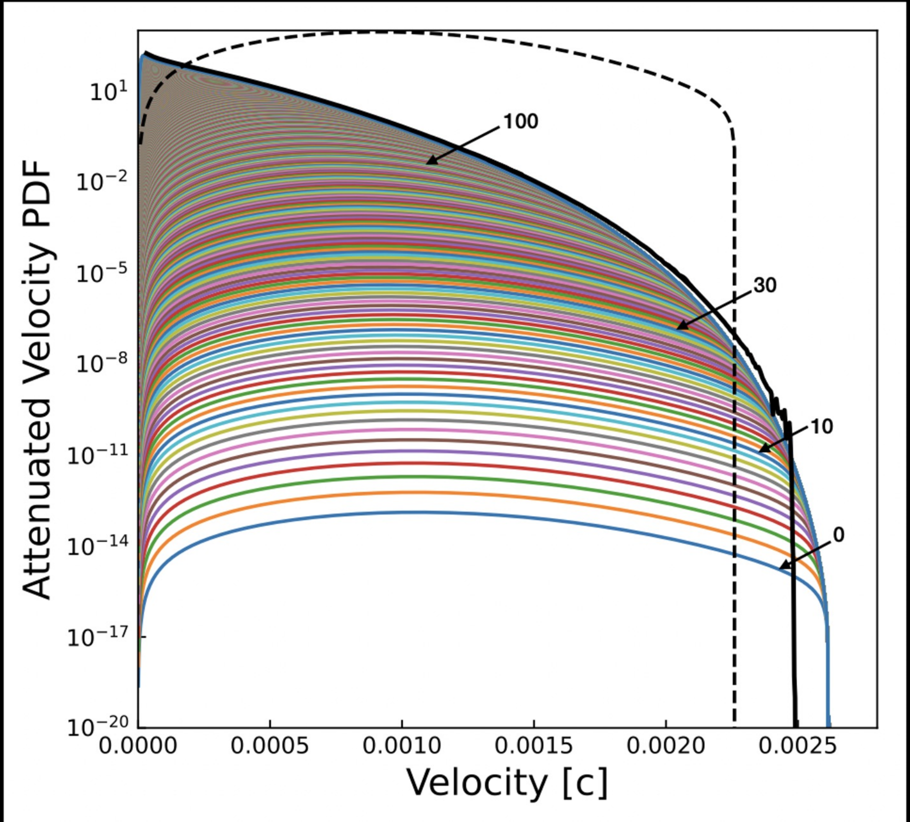
Velocity Distribution



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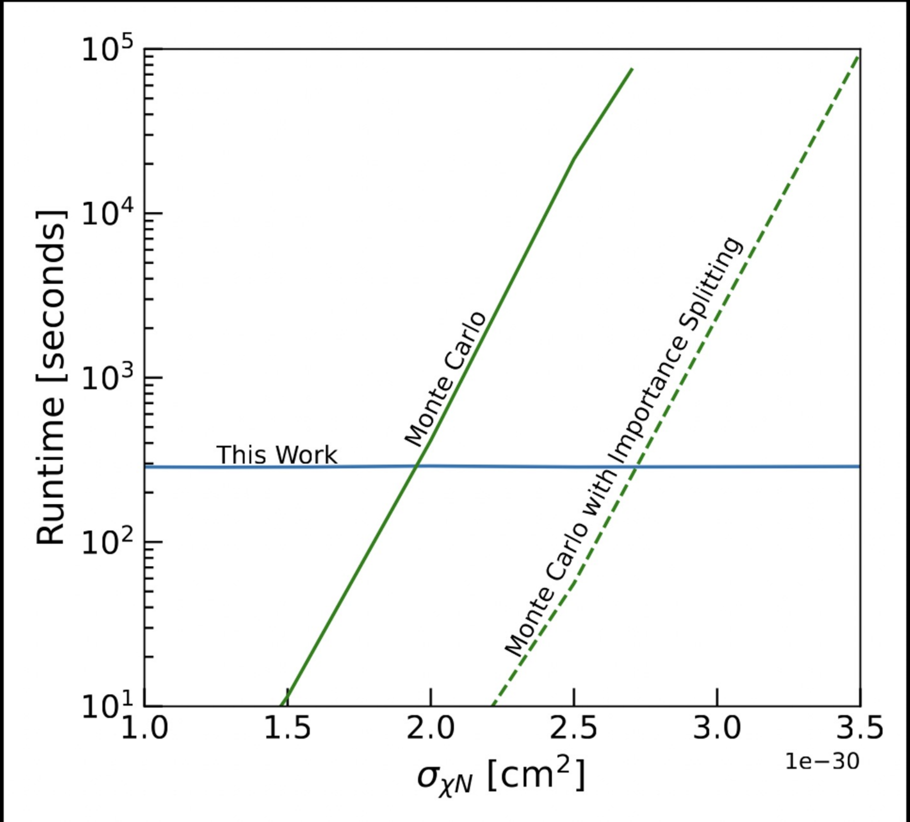
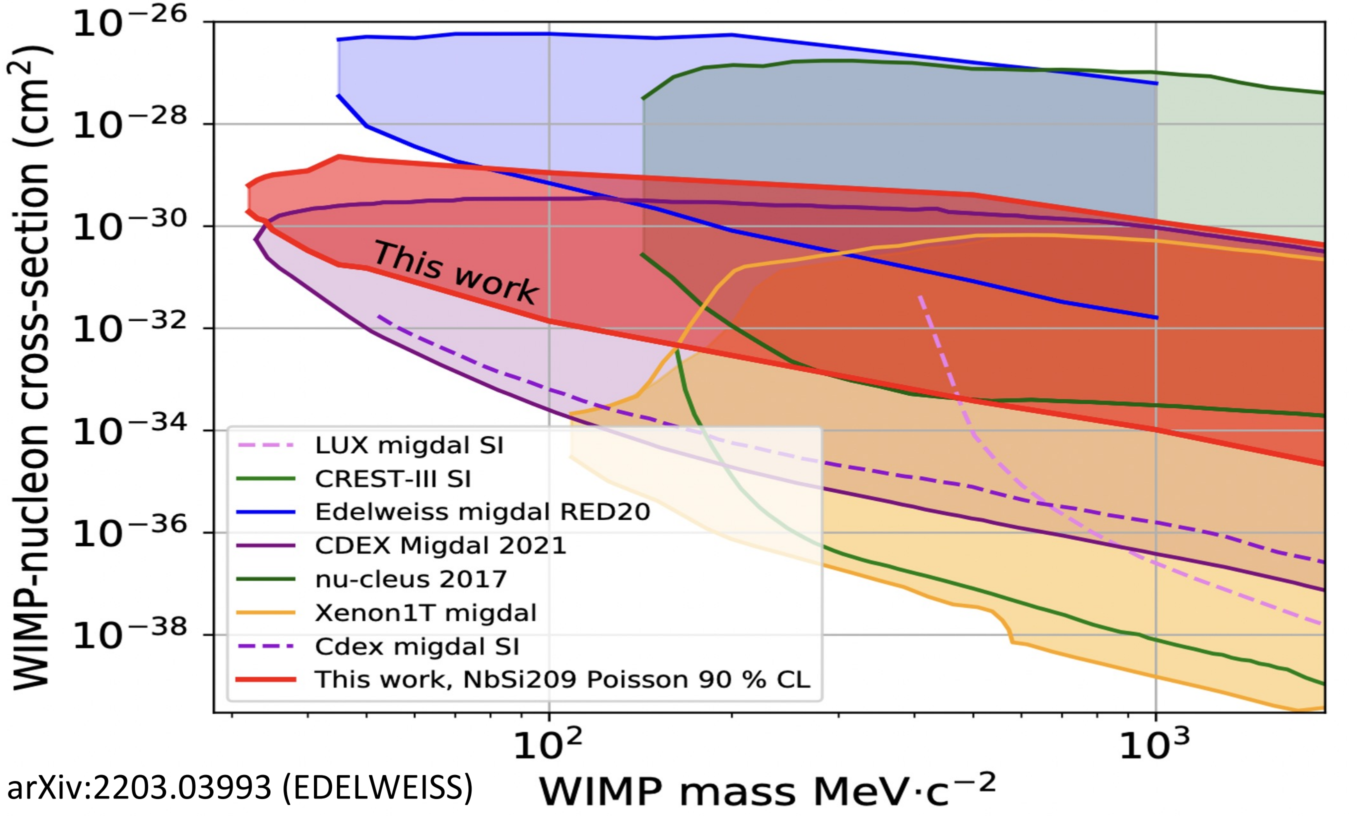
Runtime Comparison



M_X = 200 MeV
Depth = 1400 m

Attenuation: Straight Line Approximation



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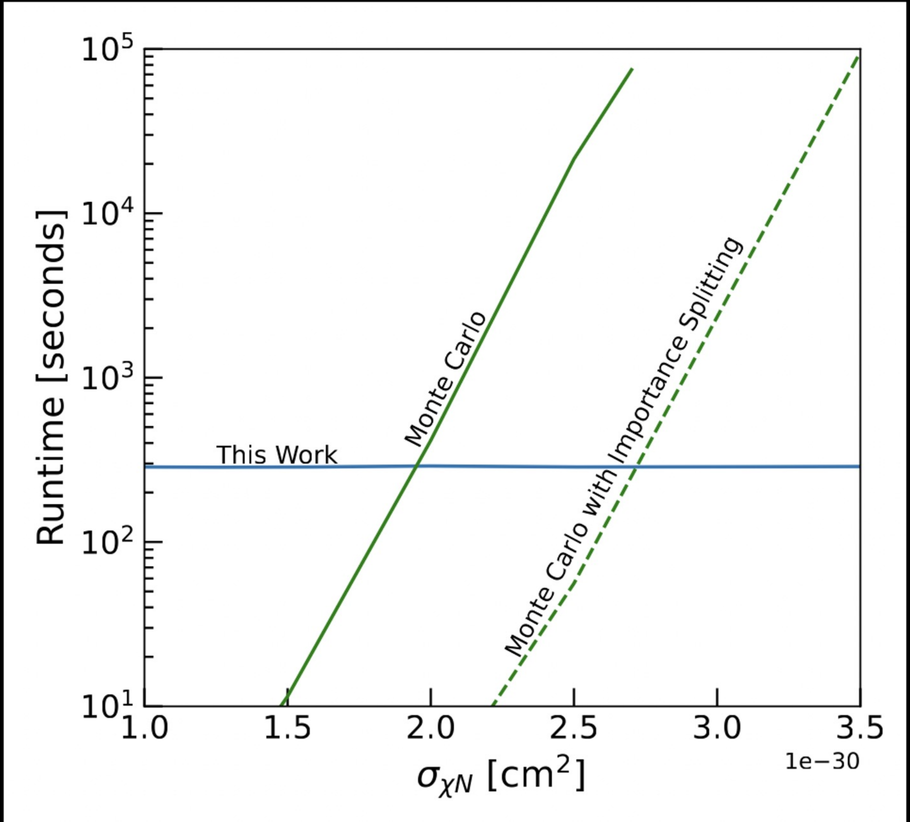

M_X = 200 MeV
Depth = 1400 m

Thank you!

Many thanks to Timon Emken for details on the DaMaSCUS Monte Carlo code

Thank you to Ivan Esteban for suggestions on speeding up integration

Code publicly available: https://github.com/ccapp413/DMpropPublic

Backup: 500 MeV, 10^{-30} cm^2