Attenuation of Boosted Dark Matter in Two Component Dark Matter Scenario

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Overview

Introduction (1/2)

- Dark matter (DM) interacts weakly with Standard Model particles, making direct detection difficult.
- Current underground detectors like XENONnT, LUX-ZEPLIN, DarkSide-20k, PandaX measure recoil energy of DM-electron/nucleus scattering, limited by the low velocity of cold DM ($\sim$ 220 km/s).
- Low DM velocity restricts detectable recoil energy in experiments.
- Stringent detection limits exist for DM masses $>$ 100 MeV, but sensitivity drops for lighter DM particles.
- Light DM particles with relativistic velocity (boosted DM) can provide higher recoil energy, making detection feasible in existing experiments.

Introduction (2/2)

- Possible sources of BDM:
  1. Interaction with cosmic rays (CR) or high energy neutrinos [Xia et al., 2022, Jho et al., 2021]
  2. Evaporation from Primordial Black Holes (PBH) [Chao et al., 2021]
  3. DSNB and Blazar BDM [Das et al., 2024, Granelli et al., 2022]
  4. Annihilation of the heavy (dominant) DM in the galactic halo at present time - *Two Component DM* [Basu et al., 2023, Li et al., 2023, Agashe et al., 2014]
- **Two Component Boosted Dark Matter Model :** Annihilation of the dominant DM species A produces the boosted dark matter B. $AA \rightarrow BB$
- In this work ([Kumar and Lekshmi, 2024]-*communicated to PRD*), we study the BDM's kinetic energy attenuation due to nuclear and electron collision for two cases; high boost ($\geq O(10^2)$) and moderate boost ($\leq O(10^2)$).

Galactic Flux of Boosted Dark Matter (1/2)

- We adopt a model independent analysis of two component dark matter scenario.
- Boost can be expressed as :

$$\gamma = \frac{1}{\sqrt{1 - v_B^2}} \sim \frac{m_A}{m_B} \tag{1}$$

- The differential flux of the boosted dark matter B from the galactic centre is [Agashe et al., 2014],

$$\frac{d\phi}{d\Omega \, dT_B} = \frac{1}{4} \frac{r_{\text{Sun}}}{4\pi} \left(\frac{\rho_{\text{local}}}{m_A} \right)^2 J \, \langle \sigma_{AA \to BB} \; v \rangle \frac{dN_B}{dT_B}, \tag{2}$$

Galactic Flux of Boosted Dak Matter (2/2)

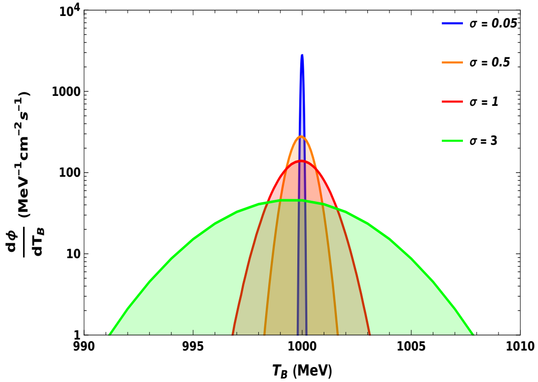


Figure: Differential flux of the boosted dark matter as a function of its kinetic energy (T_B) at different width (σ) of the normal distribution.

- $\sigma_{AA \to BB} = 1 \times 10^{-26} \mathrm{cm}^2$
- The differential energy spectrum is expressed as,

$$\frac{dN_B}{dT_B} = 2\,\delta(T_B - m_A) \qquad (3)$$

Attenuation of Boosted Dark Matter

- The rate of change of the kinetic energy of the boosted dark matter (B) with respect to the distance z is
$$\frac{dT_B}{dz} = -\sum_i n_i \int_0^{T_i^{\max}} \frac{d\sigma_{Bi}}{dT_i} T_i dT_i, \tag{4}$$
where,
$i = e, N$ for electron or nucleus species respectively.
$n_i =$ number densities.
We assume one-dimensional collision approximation.
- The differential cross section for DM-electron/nucleon collision is expressed as
$$\frac{d\sigma_{Bi}}{dT_i} = \frac{\sigma_{Bi}}{T_i^{\max}(T_B)} \tag{5}$$
- The maximal recoil energy of the the electron or the nucleon is found to be
$$T_i^{\max}(T_B) = \left[1 + \frac{(m_i - m_B)^2}{2m_i(T_B + 2m_B)}\right]^{-1} T_B. \tag{6}$$

Nuclear Scattering: Form Factor = 1 (1/2)

- The spin independent part of the DM-Nucleus cross section, σ_{BN}, is related to the atomic number (A) and DM-nucleon cross section, σ_{Bn}, as

$$\sigma_{BN}(q^2) = \frac{\mu_N^2}{\mu_n^2} A^2 \sigma_{Bn} F^2(q^2) \tag{7}$$

- Since the dominant chemical component of earth's crust is Oxygen, $m_N \approx 15$ GeV, we consider the case where $m_B, T_B << m_N$. In this limit we can write,

$$\frac{dT_B}{dz} = -\frac{1}{\ell(T_B)} \left(T_B + \frac{T_B^2}{2m_B} \right). \tag{8}$$

- Here ℓ is the mean free path for energy loss, given by,

$$\frac{1}{\ell(T_B)} = 2m_B \sum_N g_N(T_B) n_N \sigma_{BN} / m_N \tag{9}$$

Nuclear Scattering: Form Factor = 1 (2/2)

- The factor g_N is calculated by integrating the following quantity that involves the nuclear form factor as

$$g_N(T_B) = \int_0^{T_N^{\max}} F_N^2(q^2) \frac{2T_N}{(T_N^{\max})^2} dT_N. \tag{10}$$

- $g_N \to 1$ when $F_N(q^2) \to 1$.
- The analytical solution for the kinetic energy of the boosted dark matter at a distance z is,

$$T_B(z) = \frac{T_B(0)e^{-z/\ell}}{1 + \frac{T_B(0)}{2m_B}\left(1 - e^{-z/\ell}\right)}. \tag{11}$$

Nuclear Scattering: Form Factor $\neq 1$

- For the heavier nuclei, Helm form factor takes the following form:

$$F(q^2) = \frac{3j_1(qR_1)}{qR_1} e^{-\frac{1}{2}q^2 s^2} \tag{12}$$

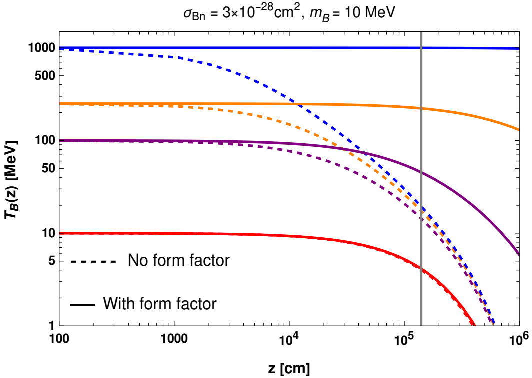
where $j_1(x)$ is the spherical Bessel function of the first kind

- The Helm form factor can be approximated as a Gaussian form factor,

$$F_N(q^2) \approx e^{-q^2/\Lambda_N^2} \quad (\text{for } qR_1 < \zeta_1), \tag{13}$$

- The flux of the BDM in terms of the attenuated kinetic energy is expressed as,

$$\left.\frac{d\phi}{dT_B}\right|_z = \frac{4m_B^2 e^{z/\ell}}{\left(2m_B + T_B - T_B e^{z/\ell}\right)^2} \left.\frac{d\phi}{dT_B}\right|_{z=0}. \tag{14}$$



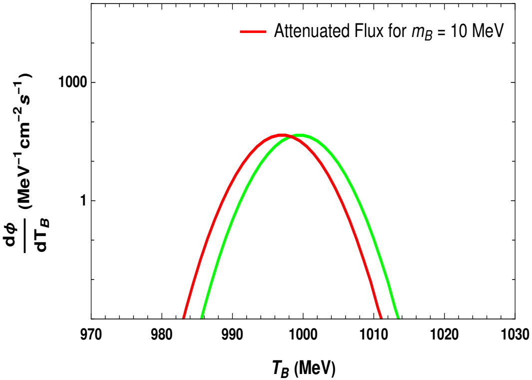


Figure: (Left) K.E of BDM as a function of z is shown for different initial values of the K.E. The gray vertical line shows $z = 1.4$ km for the XENON experiment. (Right) Initial flux (Green) and attenuated flux (Red) at $z = 1.4$ km *with form factor* ($F_N^2(q^2) \neq 1$) for $T_B = m_A = 1000 MeV$ and $m_B = 10 MeV$.

Scattering with electrons

- The analytical solution for attenuated kinetic energy for electron scattering is the same as the nuclear scattering case (without form factor).

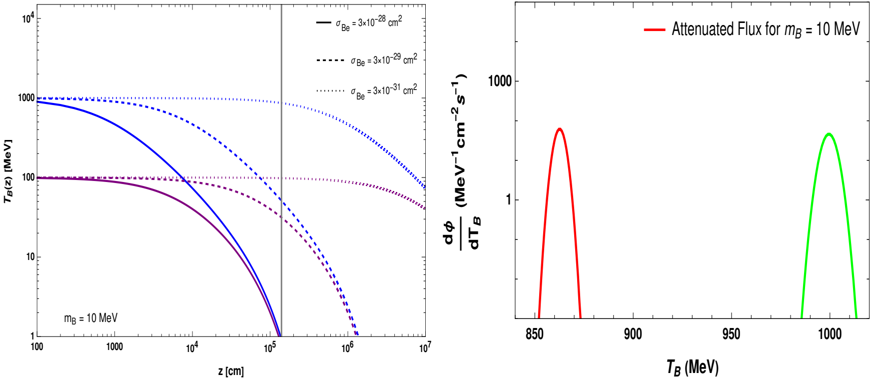


Figure: (Left) Attenuation of K.E for BDM-electron scattering $m_B = 10$ MeV. (Right) Initial flux (Green) and attenuated flux (Red) at $z = 1.4$ km in electron scattering case. $\sigma_{Be} = 3 \times 10^{-31}$ cm^2.

Conclusion (1/3)

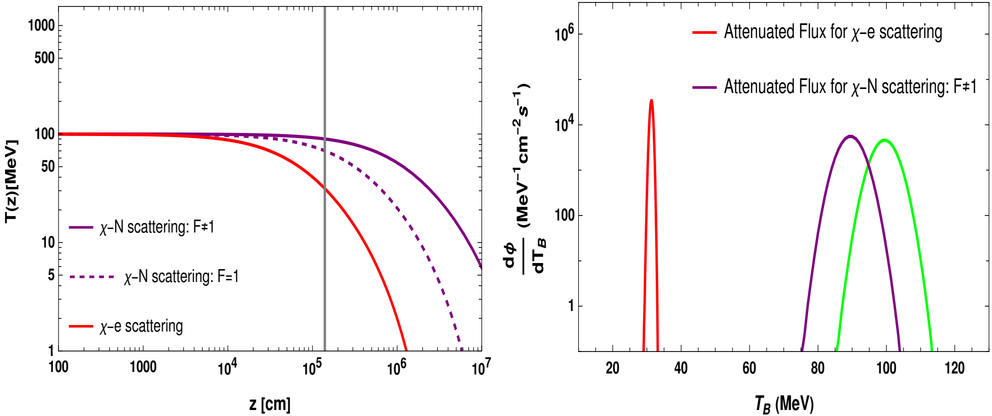


Figure: (Left) K.E of BDM as a function of z is shown for DM-nucleus scattering (with and without form factor) and DM-electron scattering. $m_B = 10$ MeV. $\sigma_{Bn} = \sigma_{Be} = 3 \times 10^{-29}$ cm^2. (Right) Initial flux (Green) and attenuated flux due to scattering with the nucleus (Purple) and electron (Red) scattering.

Conclusion (2/3)

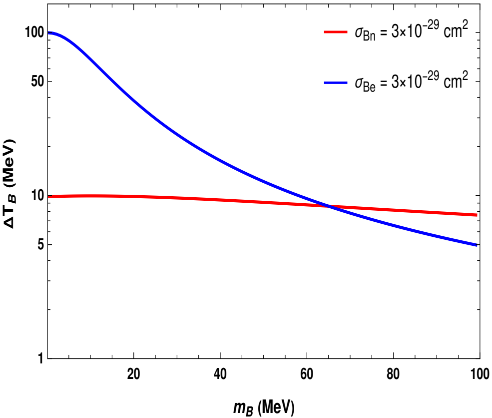


Figure: Shift in the K.E after attenuation at z = 1.4 km as a function of m_B. We have assumed the initial K.E to be 100 MeV and $\sigma_{Bn} = \sigma_{Be} = 3 \times 10^{-29}$ cm^2.

Conclusion (3/3)

- The kinetic energy of boosted dark matter (BDM) is attenuated as it travels through the Earth's crust, leading to a shift in the peak position of the BDM flux. This must be accounted for when interpreting direct detection results.
- Attenuation is highly sensitive to the masses of dark matter species, scattering cross-sections, and nuclear form factors.
- Attenuation due to BDM-electron scattering is generally stronger than BDM-nucleus scattering for MeV-scale BDM, especially for larger scattering cross-sections ($\sigma \geq 3 \times 10^{-29}\,\mathrm{cm}^2$).
- For kinetic energy > 1 GeV, inelastic scattering mechanisms may dominate and should be included in future studies for more accurate attenuation predictions.
- Considering attenuation is crucial for accurate bounds on dark matter properties from experiments like XENONnT and LUX-ZEPLIN, as the observed BDM flux peak might not directly correspond to the dominant DM mass.

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Thank You

Plots

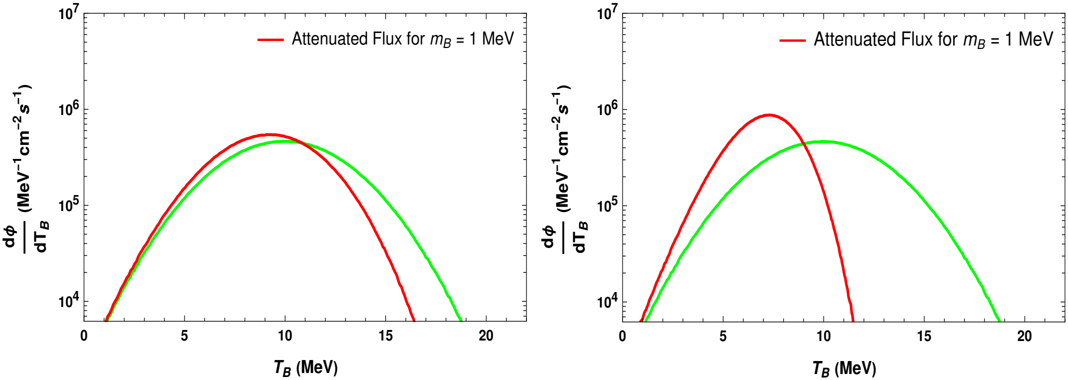

Figure: Electron and nuclear scattering case for m_A=10 MeV. $\sigma_{Be}=3\times10^{-31}$ cm^2 and $\sigma_{Bn}=3\times10^{-28}$ cm^2