Exploring Sub-GeV Dark Matter Boosted by DSNB: Insights from XENONnT and LZ Experiments

Valentina De Romeri[1], *Anirban Majumdar*[2], *Dimitrios K. Papoulias*[3], *Rahul Srivastava*[2]

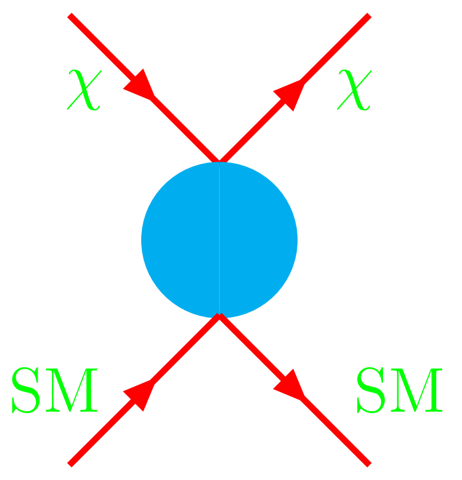
[1]Instituto de Física Corpuscular (CSIC-Universitat de València), Paterna (Valencia), Spain
[2]Indian Institute of Science Education and Research - Bhopal, Madhya Pradesh, India
[3]National and Kapodistrian University of Athens, Athens, Greece

Overview

Various cosmological observations suggest that 85% matter of the Universe is cold dark matter (DM), a non-luminous substance that does not interact with photons and only "weakly" with ordinary matter. Despite no conclusive DM discovery, various experiments, including direct and indirect detection experiments and collider searches, have imposed very tight constraints on its properties. However, these experiments primarily explore the DM parameter space within the GeV-TeV mass range. Recently, interest in detecting sub-GeV DM has increased. However, their low momenta make detection challenging, as they fail to induce recoils above the thresholds of conventional direct detection experiments. Even strongly interacting DM within this mass range has been suggested to elude all observational bounds. Here we explore a scenario where sub-GeV cold DM particles are accelerated to semi-relativistic velocities through their scattering with the diffuse supernova neutrino background (DSNB) in the galaxy [1]. This mechanism introduces a high energy DM component capable of interacting with both electrons and nuclei in the detector, triggering a detectable recoil signal. We analyze data from the most advanced direct detection facilities in the contemporary world, namely the XENONnT [2] and LUX-ZEPLIN (LZ) [3] experiments, to derive constraints on the scattering cross sections of sub-GeV boosted DM with both electrons and nucleons. Additionally, we emphasize the imperative nature of considering Earth's attenuation effects for both electron and nuclei interactions. Lastly, we present a comparison of our findings with existing constraints, illuminating the complementarity and significance of the LZ and XENONnT data in probing the sub-GeV DM parameter space.

Direct Detection In a Nutshell

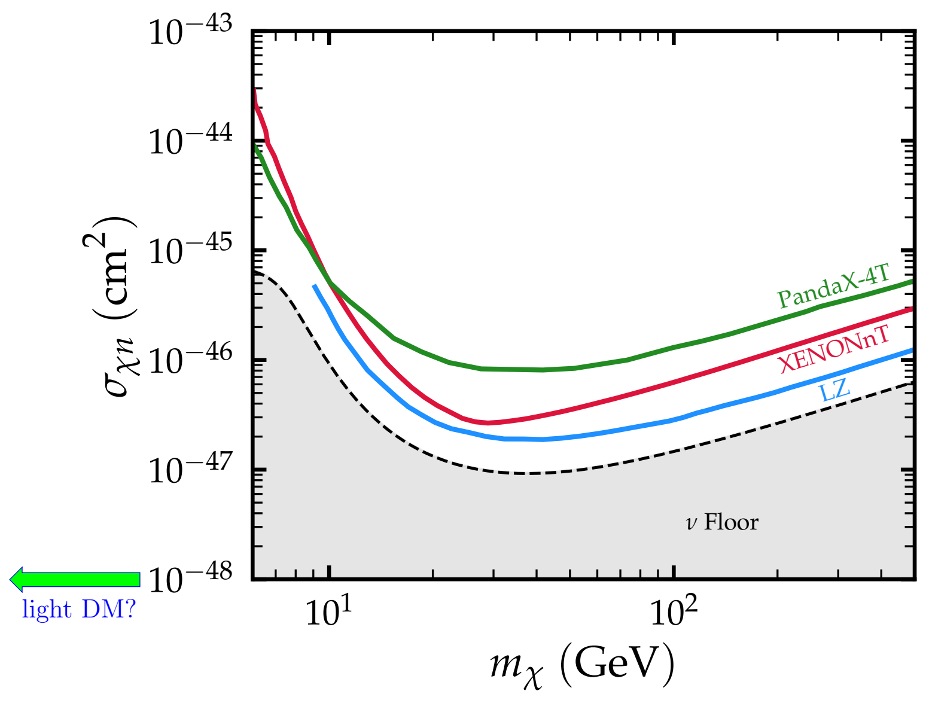
In the Direct Detection experiments, DM particles are identified by observing the recoil energy of target nuclei or electrons, triggered by their interaction with surrounding DM particles and estimating the energy deposited by the scatterer through backtracing the emitted scintillation signals. These detectors are strategically placed underground to provide a shield against cosmic particles, particularly Cosmic muons, to reduce background.



A Vast Experimental Effort

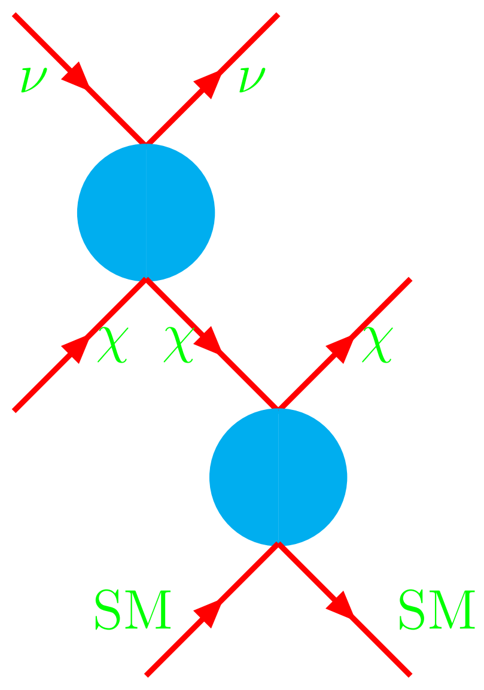
For decades, Direct Detection experiments have predominantly targeted DM particles with a mass around the electroweak scale ($m_\chi = 100$ GeV) possessing weak scale couplings, known as WIMPs. Unfortunately, despite significant experimental endeavours, these WIMP particles remain elusive. Currently, only a tiny region of the WIMP parameter space $(\sigma_{\chi n}, m_\chi)$ remains unexplored above the neutrino floor. This motivates physicists to explore sub-GeV DM particles. However, their low momenta (see Eq. 1) make detection challenging, as they fail to induce recoils above the thresholds of conventional direct detection experiments.

$$T_r^{\max} \approx \frac{Q^2}{2m_T} \approx \frac{2m_\chi^2 m_T v_\chi^2}{(m_\chi + m_T)^2}\,. \tag{1}$$



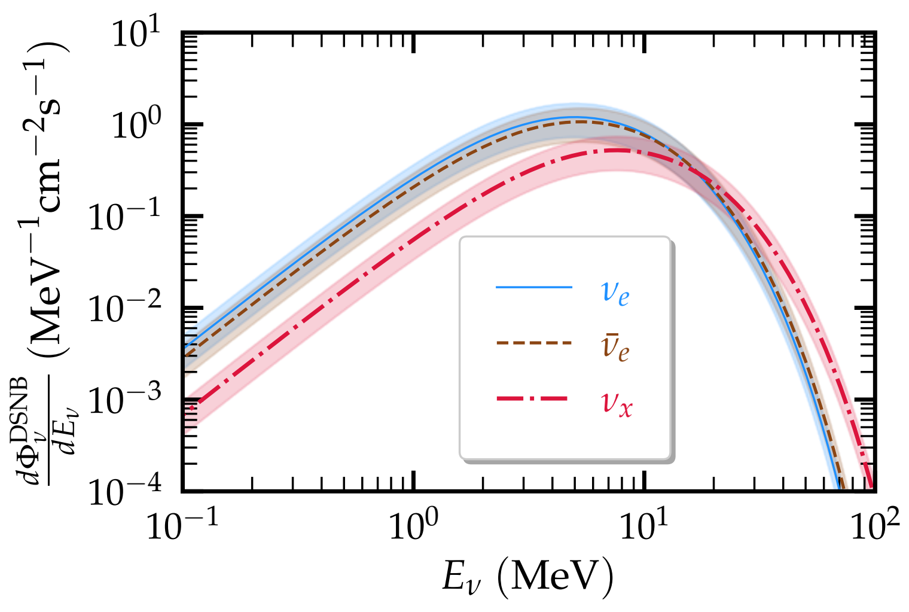
Direct Detection of Low Mass Fast Moving Dark Matter

To probe Sub-GeV DM with the current experimental facilities, we explore a scenario where sub-GeV cold DM particles are accelerated to semi-relativistic velocities through their scattering with the DSNB in the galaxy.



DSNB Neutrinos

Right after the first star formation event, the Universe was surrounded by an isotropic flux of MeV energy neutrinos and antineutrinos of all flavours, produced from all supernovae events from the core-collapse explosions of huge stars throughout the Universe. This cumulative and isotropic flux of MeV neutrinos forms DSNB.



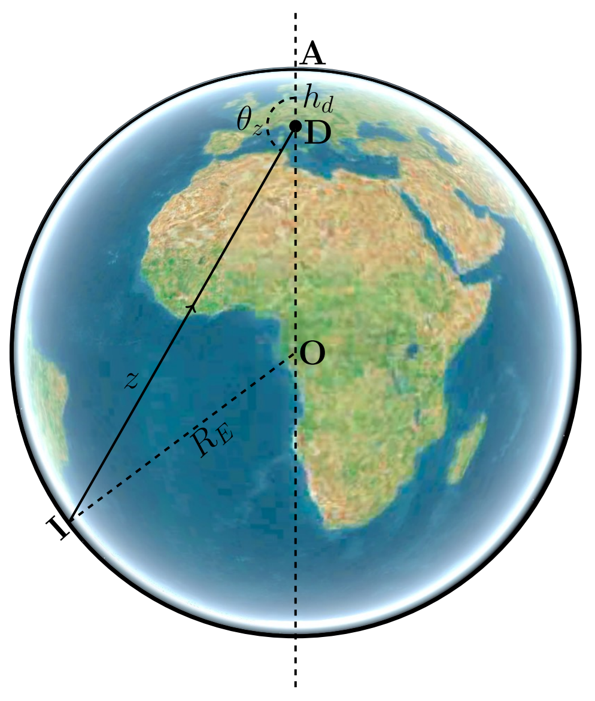
Boosted Dark Matter Flux At The Underground Detectors

The DSNB-boosted DM differential flux can be expressed as,

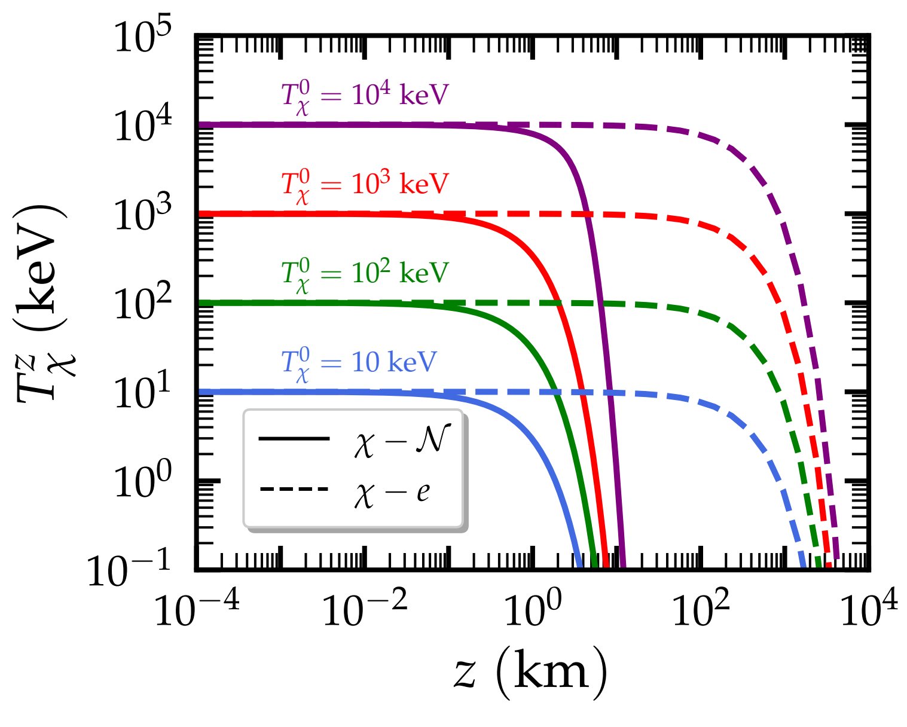
$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm halo}\int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{1}{m_\chi}\frac{d\sigma_{\nu\chi}}{dT_\chi}\frac{d\Phi_\nu^{\rm DSNB}}{dE_\nu} \tag{2}$$

Earth's Attenuation: Before reaching the underground detector, DSNB-boosted DM flux may lose its energy during its propagation through the Earth. The effect of Earth's attenuation can be accounted for via the energy loss equation,

$$\frac{dT_\chi^z}{dz} = -\,n_i \int_0^{T_i^{\max}(T_\chi^z)} \frac{d\sigma_{\chi i}}{dT_i} T_i\, dT_i \tag{3}$$



The effect of attenuation can be visualized from the following figure, where DSNB-boosted DM's underground kinetic energy (T_χ^z) is demonstrated as a function of the distance (z) while considering several initial values of the DM kinetic energy at Earth's surface (T_χ^0), assuming $m_\chi = 300$ MeV, and $\sigma_{\chi e} = \sigma_{\chi n} = 10^{-29}$ cm^2.



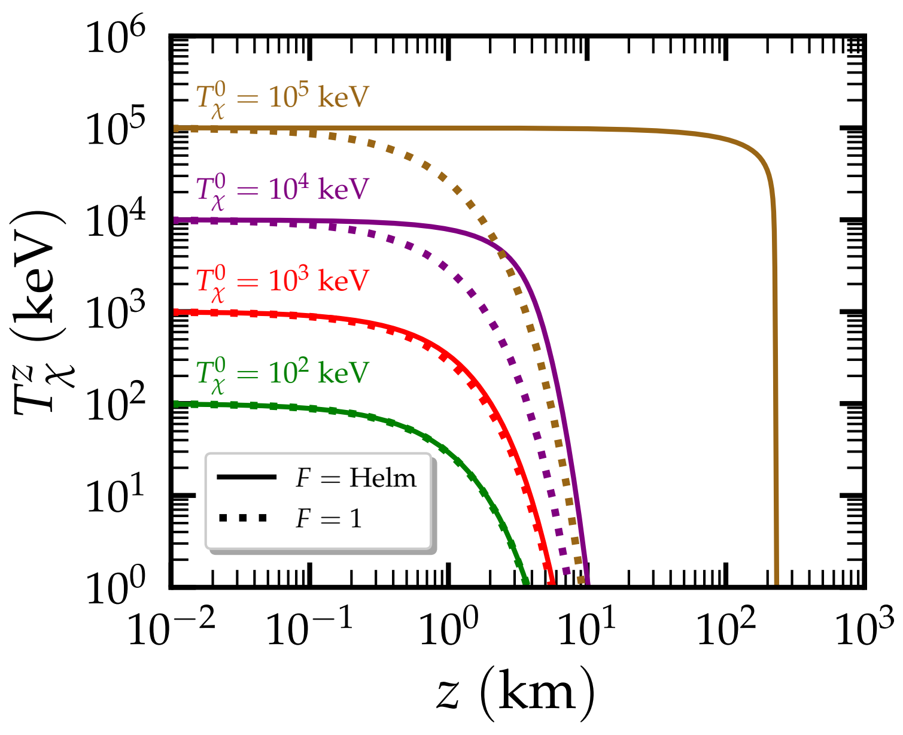
Effect of the finite nuclear size: For the case of DM-nucleus scattering, the spin-independent (SI) DM-nucleus elastic scattering cross section is expressed as:

$$\sigma_{\chi\mathcal{N}}^{\rm SI}(q^2) = \frac{\mu_{\chi\mathcal{N}}^2}{\mu_{\chi n}^2} A^2 \sigma_{\chi n} F^2(q^2)\,. \tag{4}$$

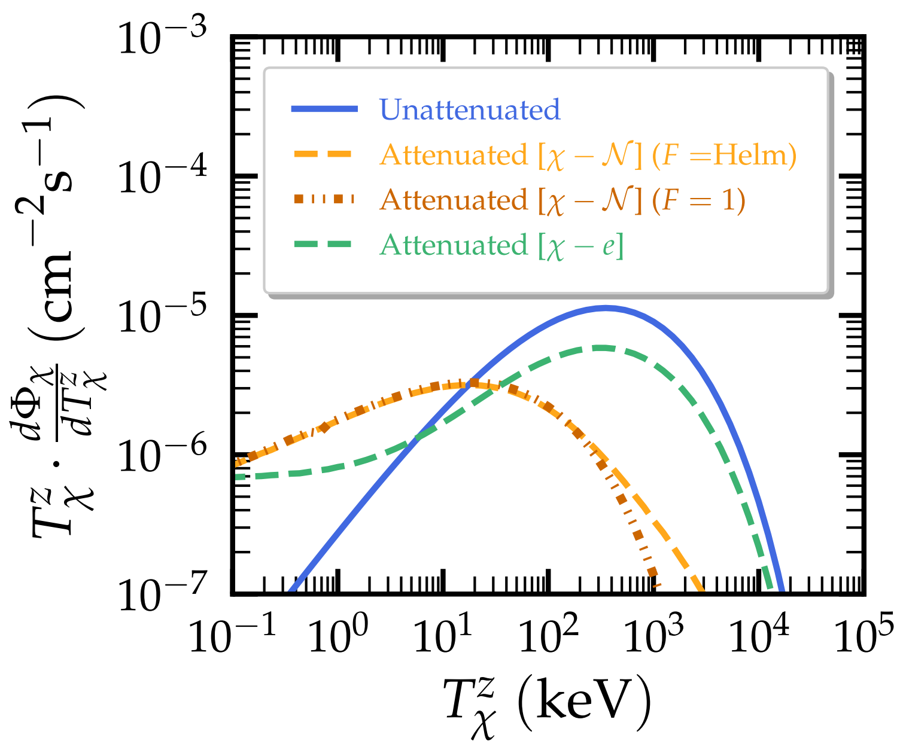
Nuclear form factor, $F(q^2)$, accounts for the finite nuclear size, and we consider a Helm-type effective form factor, which can be read as,

$$F(q^2) = \frac{3j_1(qR_0)}{qR_0}\, e^{\left[-\frac{1}{2}(qs)^2\right]}\,. \tag{5}$$

When solving Eq. 3 for the case of $\chi - \mathcal{N}$ scattering, the inclusion of a Helm-type nuclear form factor is particularly relevant for high-energy DSNB-boosted DM particles, compared to the case where we completely neglect nuclear effects, i.e., $F = 1$.

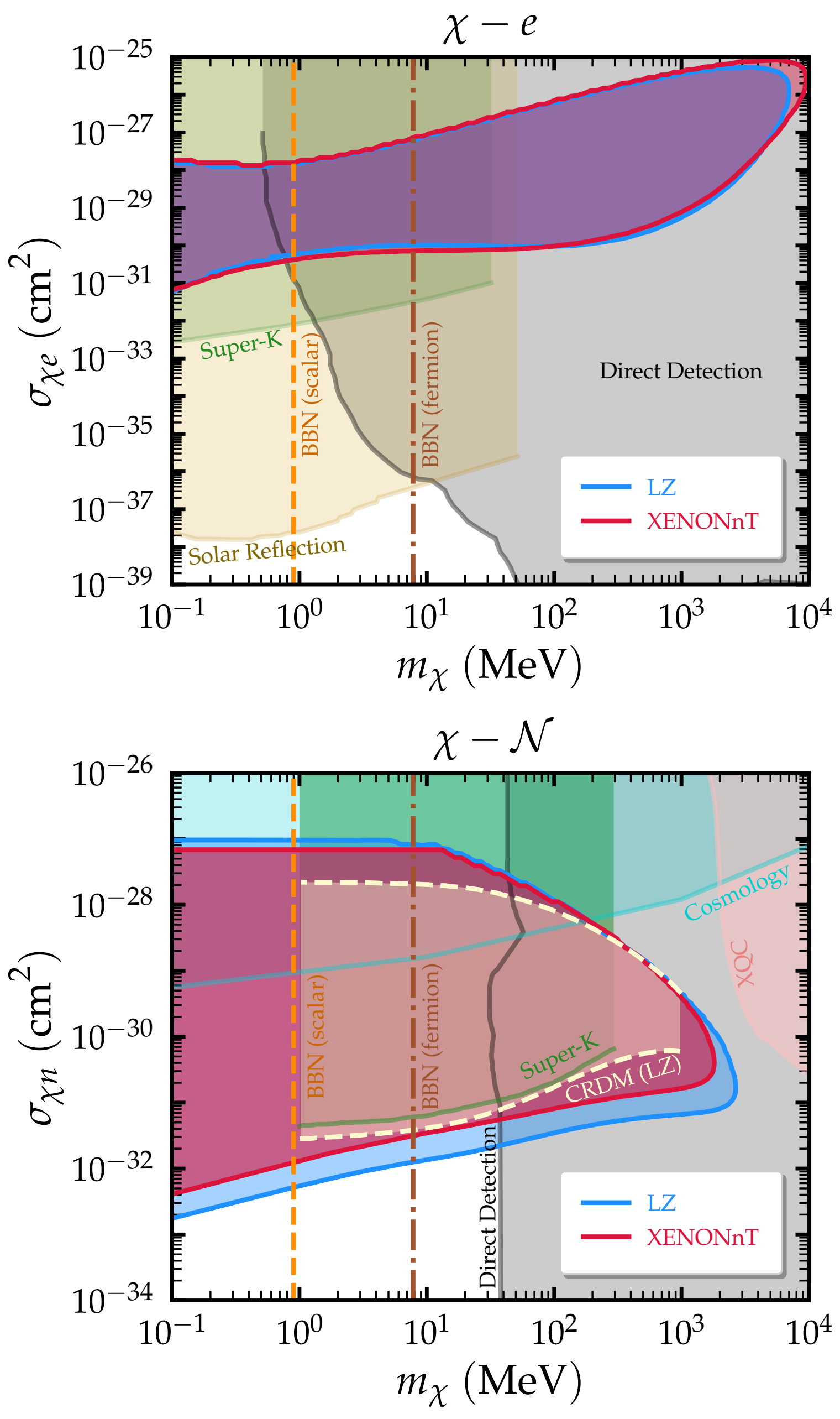


To further visualize the Earth attenuation and finite nuclear size effects, we demonstrate the DSNB-boosted DM flux for unattenuated and attenuated cases in the following diagram, assuming $m_\chi = 300$ MeV, and $\sigma_{\chi e} = \sigma_{\chi n} = 10^{-29}$ cm^2.



Results

We present in following figure the 90% C.L. exclusion regions on the DSNB-boosted DM, in the planes $(m_\chi, \sigma_{\chi e})$, for the benchmark $\sigma_{\nu\chi} = \sigma_{\chi e}$ and $(m_\chi, \sigma_{\chi n})$, for the benchmark $\sigma_{\nu\chi} = \sigma_{\chi n}$. We consider the case of DM scattering off electrons and nuclei and show both constraints obtained using LZ (blue) and XENONnT (red) experimental data.



Summary of the Results

- DSNB Boosted DM produces a subdominant, semi-relativistic component of Galactic DM, which gives us the opportunity to probe the Sub-GeV DM parameter space
- Although a significant part of our constraints lie in a region of parameter space already probed by other searches, these results highlight the complementarity and significance of the LZ and XENONnT data in probing the sub-GeV DM parameter space.
- Consideration of Earth attenuation and finite nuclear size effects are crucial for accurate interpretation of experimental results.

References

[1] V. De Romeri, **A. Majumdar**, D. K. Papoulias and R. Srivastava, "XENONnT and LUX-ZEPLIN constraints on DSNB-boosted dark matter," `arXiv:2309.04117 [hep-ph]`.

[2] E. Aprile *et al.* [XENON Collaboration], "First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment," Phys. Rev. Lett. **131** (2023) no.4, 041003, `arXiv:2303.14729 [hep-ex]`.

[3] J. Aalbers *et al.* [LZ Collaboration], "First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment," Phys. Rev. Lett. **131** (2023) no.4, 041002, `arXiv:2207.03764 [hep-ex]`.