Exploring DSNB boosted sub-GeV dark matter: insights from XENONnT and LZ experiments

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Introduction

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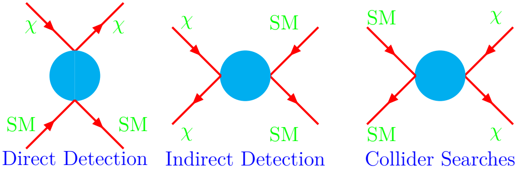
Motivation for searching the Dark Matter (DM)

- Cold DM: It is a non-luminous matter which occupies 27% of the mass and energy in the observable Universe. It does not interact with photons and interacts only "weakly" with ordinary matter.
- Astronomical and cosmological observations at various scales:
  (i) Rotation curves of spiral galaxies and galaxy clusters
  (ii) Gravitational lensing
  (iii) Cosmic Microwave background (CMB) fluctuations



- **Direct Detection Experiments:** *XENONnT, LUX-ZEPLIN, Super-CDMS, Dark-Side, PandaX-4T, etc.*
- **Indirect Detection Experiment:** *IceCube, HESS, MAGIC, etc.*
- **Accelerator searches:** *ATLAS, CMS at CERN*

DM landscape: a wide mass range

Ultralight
(QCD) axion, hidden photon, scalar field, fuzzy, non-thermal

Superlight
sterile ν, axino, warm DM, can be **thermal**

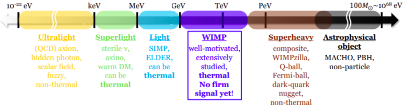
Light
SIMP, ELDER, can be **thermal**

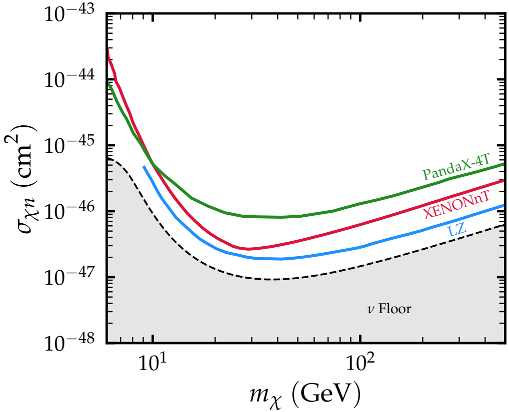
WIMP
well-motivated, extensively studied, **thermal**
No firm signal yet!

Superheavy
composite, WIMPzilla, Q-ball, Fermi-ball, dark-quark nugget, non-thermal

Astrophysical object
MACHO, PBH, non-particle

DM landscape: a wide mass range





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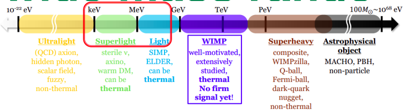

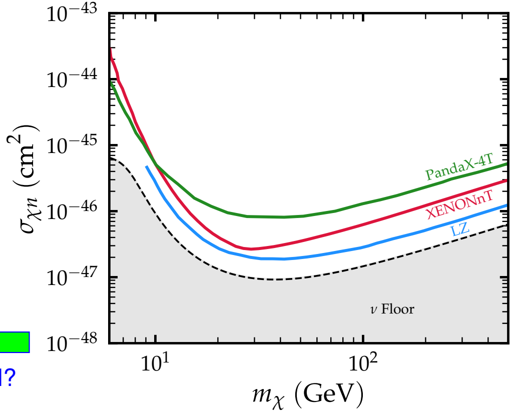

light DM?

Thermal relic DM vs boosted DM

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The maximum recoil energy of the target:

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

Thermal relic DM vs boosted DM

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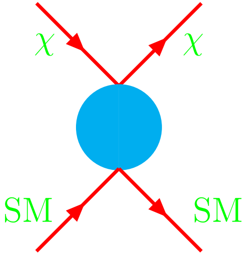

$$v_\chi \approx 10^{-3} c$$

Thermal relic DM vs boosted DM

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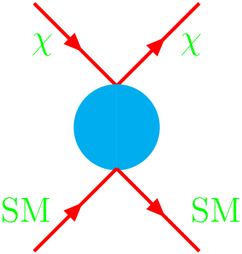
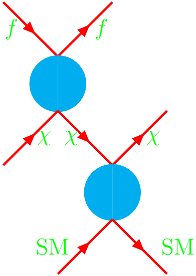




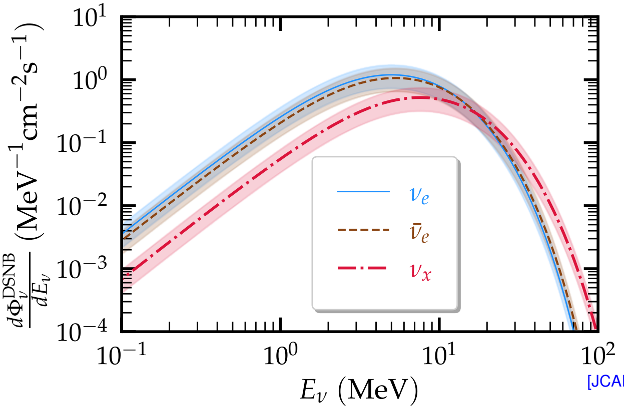
$v_\chi \approx 10^{-3} c$

$v_\chi \sim c$

DSNB boosted dark matter

Diffuse Supernova Neutrino Background

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



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BDM Flux At The Underground Detectors

The DSNB-boosted DM differential flux,

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

- $D_{\rm halo}$ encodes the line of sight integral of DM density within our galactic halo,

$$D_{\rm halo} = \int_{\Delta\Omega} \frac{d\Omega}{4\pi} \int_0^{\ell_{\rm max}} \rho_{\rm NFW}[r(\ell,\psi)]d\ell$$

- We consider Navarro-Frenk-White (NFW) profile for galactic DM density,

$$\rho_{\rm NFW}(r) = \rho_\odot \left[\frac{r}{r_\odot}\right]^{-1} \left[\frac{1+\frac{r_\odot}{r_s}}{1+\frac{r}{r_s}}\right]^2$$

- For the differential cross section, we assume the constant cross section approximation, i.e.

$$\frac{d\sigma_{\nu\chi}}{dT_\chi} = \frac{\sigma_{\nu\chi}}{T_\chi^{\rm max}}$$

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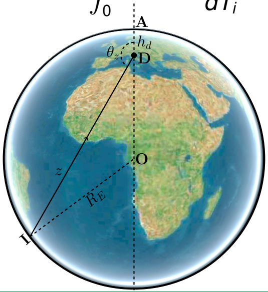
DM flux gets attenuated by the elements of the atmosphere and Earth before reaching to the underground detector. However as $n_i^{\rm atm} << n_i^{\rm Earth}$, we have **neglected the attenuation due to elements of the atmosphere**.

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



$$\frac{d\sigma_{\chi i}}{dT_i} = \frac{\sigma_{\chi i}}{T_i^{\rm max}}$$

$$i \equiv \{e, \mathcal{N}\}$$

BDM Flux At The Underground Detectors

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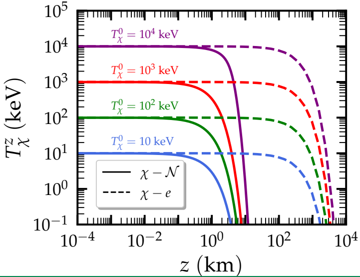
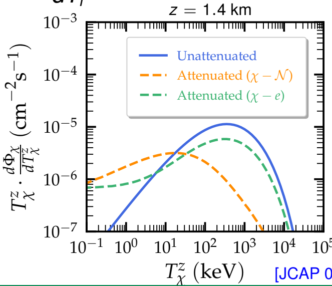
$\sigma_{\nu\chi} = \sigma_{\chi e} = \sigma_{\chi n} = 10^{-29}$ cm^2

$m_\chi = 300$ MeV





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Implications of nuclear form factor

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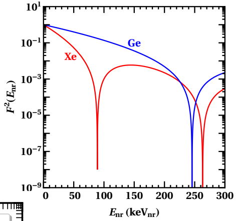
The spin independent DM-nuclei scattering cross section can be written as,

$$\sigma^{\rm SI}_{\chi\mathcal{N}}(q^2) = \frac{\mu^2_{\chi\mathcal{N}}}{\mu^2_{\chi n}} A^2 \sigma_{\chi n} F^2(q^2)$$



(Helm, 1956)

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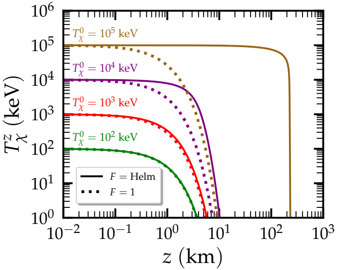

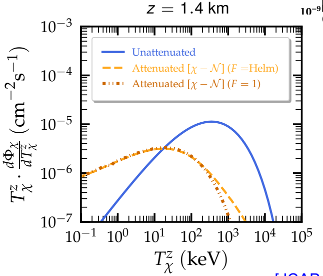

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DM signal at the underground detectors

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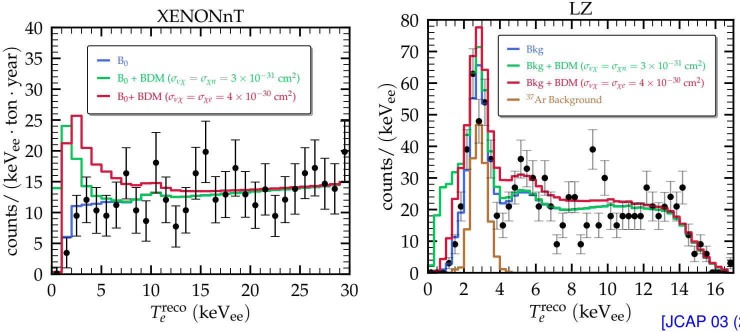
After reaching the underground detector, the DSNB-boosted DM can scatter off both the electrons and nuclei of the target material, triggering both electronic and nuclear recoils. The differential event rate with respect to the recoil energy T_i can be written as,

$$\frac{dR}{dT_i} = t_{\rm run} N^i_{\rm target} \mathcal{A} \int dT^z_\chi \frac{d\Phi_\chi}{dT^z_\chi} \frac{d\sigma_{\chi i}}{dT_i}$$

$m_\chi = 300$ MeV



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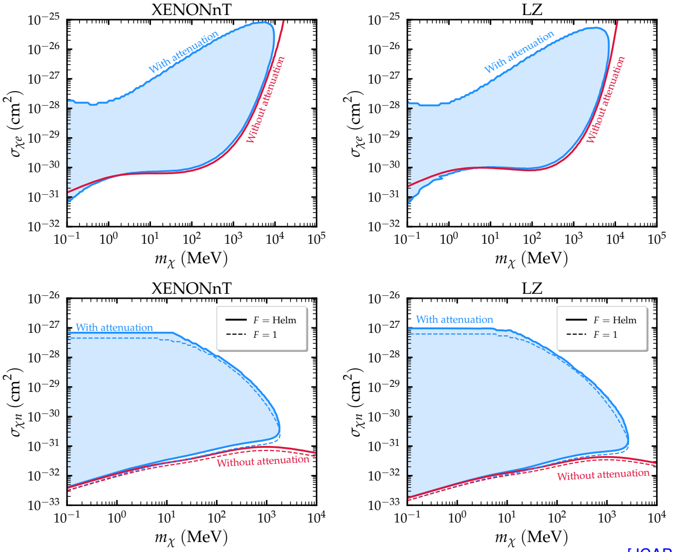
Effect of Earth attenuation in the resulting limits



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Resulting Limits

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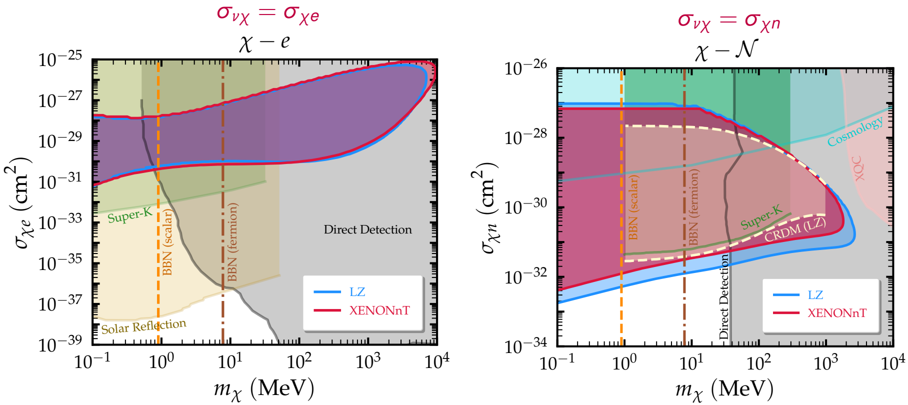

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Conclusions

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- DSNB Boosted DM produces a subdominant, semi-relativistic component of Galactic DM.
- Consideration of Earth attenuation is crucial for accurate interpretation of experimental results.
- ***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.***

THANK YOU

Extras

χ^2 function utilized

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- For the analysis of LZ data, we have performed a spectral analysis using the following Poissonian χ^2 function

$$\chi^2(\vec{\mathcal{S}};\alpha,\beta,\delta) = 2\sum_{i=1}^{51}\left[R^i_{\rm pred}(\vec{\mathcal{S}};\alpha,\beta,\delta) - R^i_{\rm exp} + R^i_{\rm exp}\ln\left(\frac{R^i_{\rm exp}}{R^i_{\rm pred}(\vec{\mathcal{S}};\alpha,\beta,\delta)}\right)\right] + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\delta}{\sigma_\delta}\right)^2,$$

- The following Gaussian χ^2 function is used for the analysis of XENONnT data

$$\chi^2(\vec{\mathcal{S}};\beta) = \sum_{i=1}^{30}\left(\frac{R^i_{\rm pred}(\vec{\mathcal{S}};\beta) - R^i_{\rm exp}}{\sigma^i}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2$$

Geophysical properties of Earth

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We model the Earth's interior as a sphere of constant electron and nuclear densities ($n_e = 8 \times 10^{23}\ \mathrm{cm}^{-3}$ and $n_{\mathcal{N}} = 3.44 \times 10^{22}\ \mathrm{cm}^{-3}$), based on the abundances of the main elements as shown in following table.

Element	**Mass Number (A)**	**Relative Abundance (%)**	$\mathbf{n}_{\mathcal{N}}$ $(\mathbf{cm}^{-3})$
Fe	55.845	32.1	6.11×10^{22}
O	15.999	30.1	3.45×10^{22}
Si	28.086	15.1	1.77×10^{22}
Mg	24.305	13.9	1.17×10^{22}
S	32.065	2.9	2.33×10^{21}
Ca	40.078	1.5	7.94×10^{20}
Al	26.982	1.4	1.09×10^{21}