Boosted dark matter from semi-annihilations in the galactic center

Takashi Toma (Kanazawa U.)

What is dark matter? @ online
25th Apr. 2025

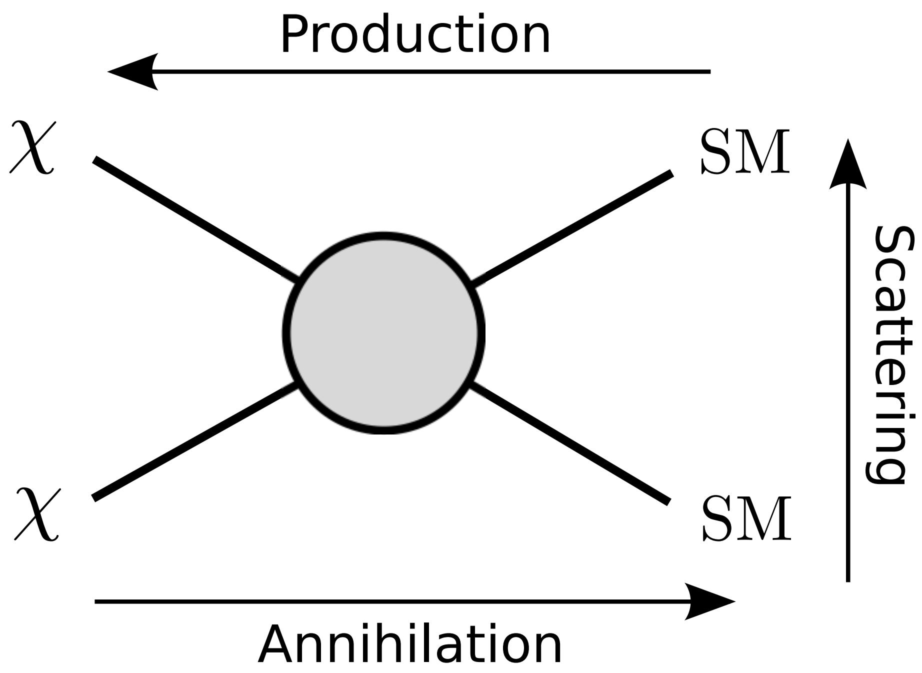
Publicly Offered Research

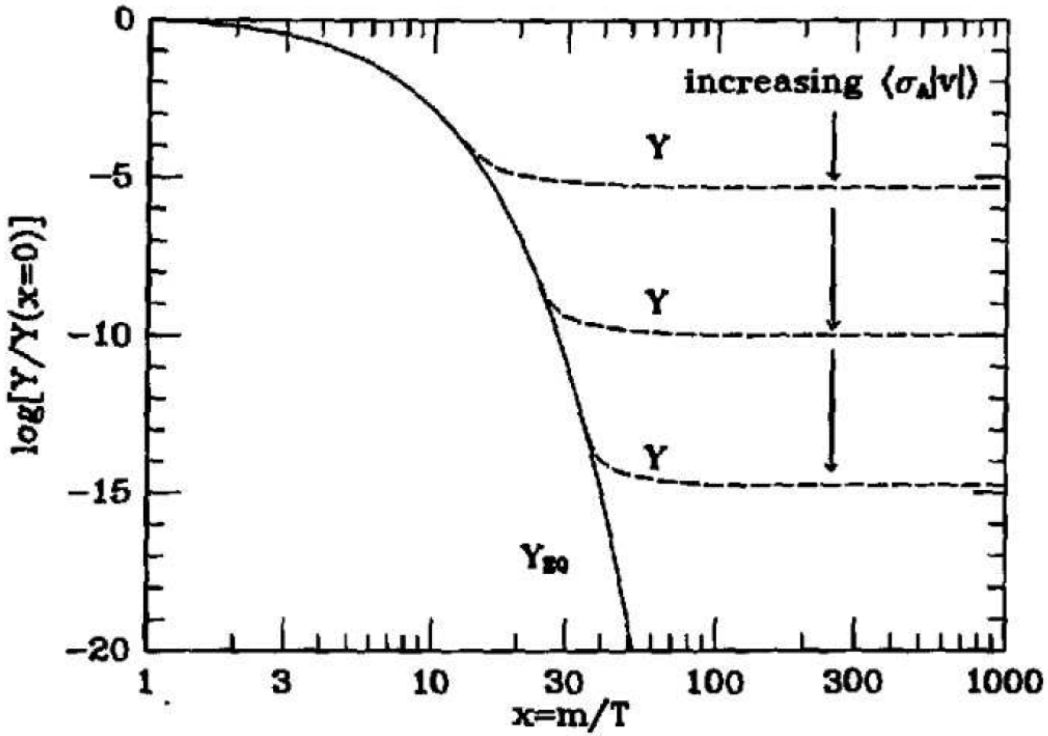
Based on Phys. Lett. B **864** 139425 (2025)
In collaboration with B. Betancourt Kamenetskaia, M. Fujiwara, A. Ibarra

Papers in FY2024

- Electric dipole moments of charged leptons in models with pseudo-Dirac sterile fermions, Asmaa Abada, TT, JHEP 08 (2024) 128 [2405.01648 [hep-ph]].
- Minimal dark matter in SU(5) grand unification, TT, Phys.Rev.D 111 (2025) 5, L051701 [2412.19660 [hep-ph]].
- Boosted dark matter from semi-annihilations in the galactic center, Boris Betancourt Kamenetskaia, Motoko Fujiwara, Alejandro Ibarra, TT, Phys.Lett.B 864 (2025) 139425 [2501.12117 [hep-ph]].

Thermal dark matter

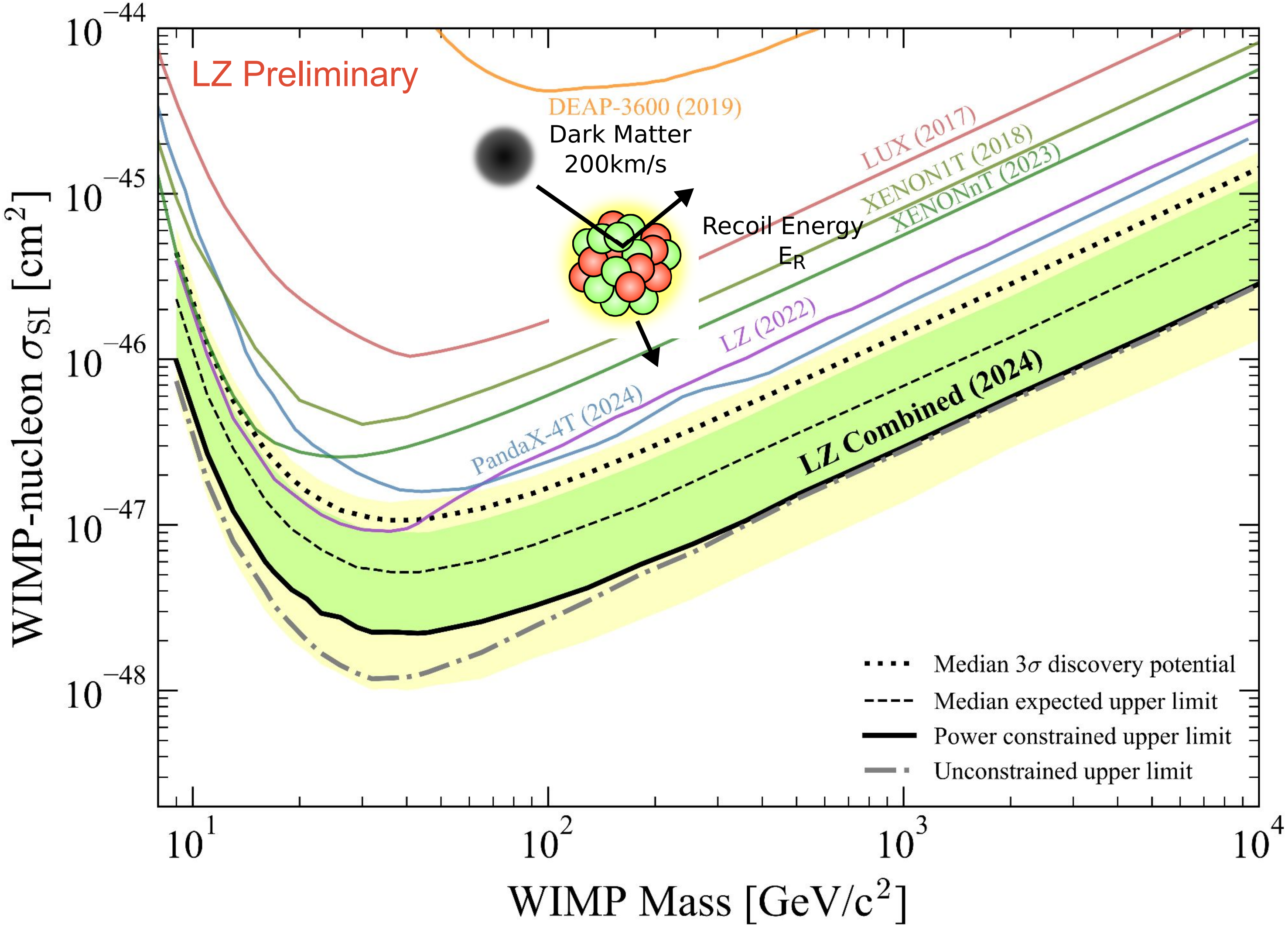


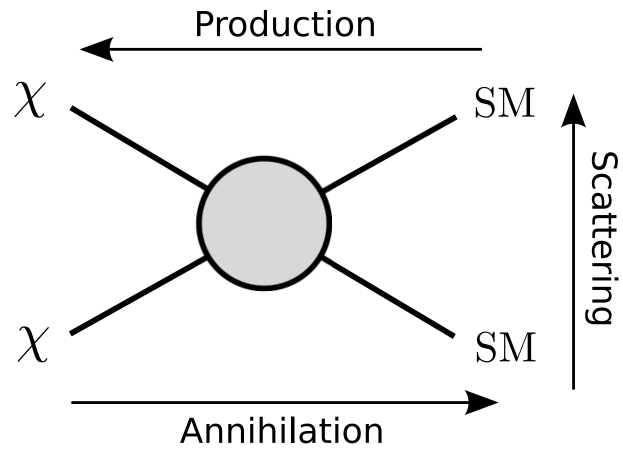


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$

- Thermalized with SM particles in early universe.
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}$cm^3/s $\sim 10^{-36}$cm^2 (only log dependent on DM mass)
- Mass range: 10 MeV – 100 TeV

Status of direct detection experiments





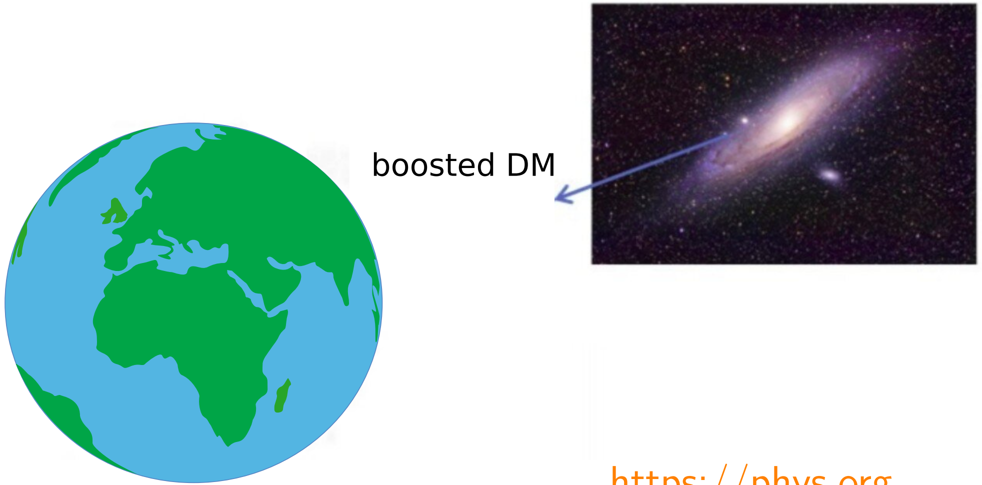
- $\Omega h^2 = 0.12$
  $\Leftrightarrow \sigma_{\rm el} \sim 10^{-36}$ cm^2
  $(\sigma_{\rm el} \lesssim 10^{-45}$ cm$^2)$
  (loop)

LZ talk @ TeVPA2024

- LZ gives the strongest bound 2.2×10^{-48} cm^2 at 43 GeV.
- Low sensitivity at low DM mass due to experimental threshold

Mechanisms to boost DM

- Semi-annihilations $\chi\chi \to \overline{\chi}\phi$ $(v_\chi = \mathcal{O}(0.1-1))$
  $\Rightarrow$ Simple and small uncertainties



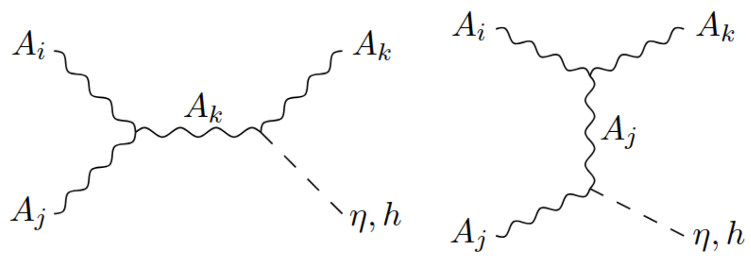
https://phys.org

Other mechanisms

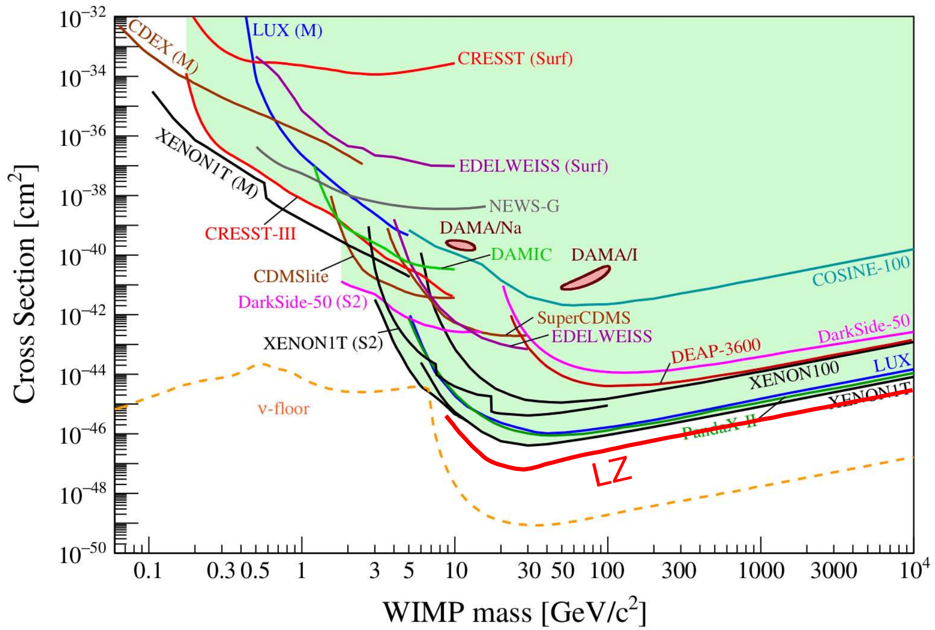
- SIMP: $\chi\chi\chi \to \chi\overline{\chi}$
- Decay or annihilations of heavy particles (non-minimal dark sector) $\chi_2\chi_2 \to \chi_1\chi_1$ $(m_{\chi_2} \gg m_{\chi_1})$
- Cosmic-ray boosted DM — Bringmann and Pospelov, PRL (2019), arXiv:1810.10543
- Blazer boosted DM
- Solar reflection of DM
- Vacuum decay

Boosted DM from semi-ann.

- Semi-annihilations: T. Hambye, JHEP 01 (2009) 028, F. D'Eramo and J. Thaler, JHEP 06 (2010) 109
  $A_i A_j \to A_k h$



- We focus on $\chi\chi \to \overline{\chi}\nu$
- DM energy in the final state: $E_\chi = \frac{5}{4} m_\chi$ (monochromatic)
  $\Rightarrow$ Moderate boost factor $\gamma_\chi \equiv \frac{E_\chi}{m_\chi} = \frac{5}{4} = 1.25 \; (v_\chi = 0.6)$
- Certain recoil energy can be induced by BDM even for sub-GeV DM mass
- No deep inelastic scattering
  $\Rightarrow$ simple calculation



J. Billard et al., Rept.Prog.Phys. 85 (2022) 5, 056201

Scattering with nuclei for BDM

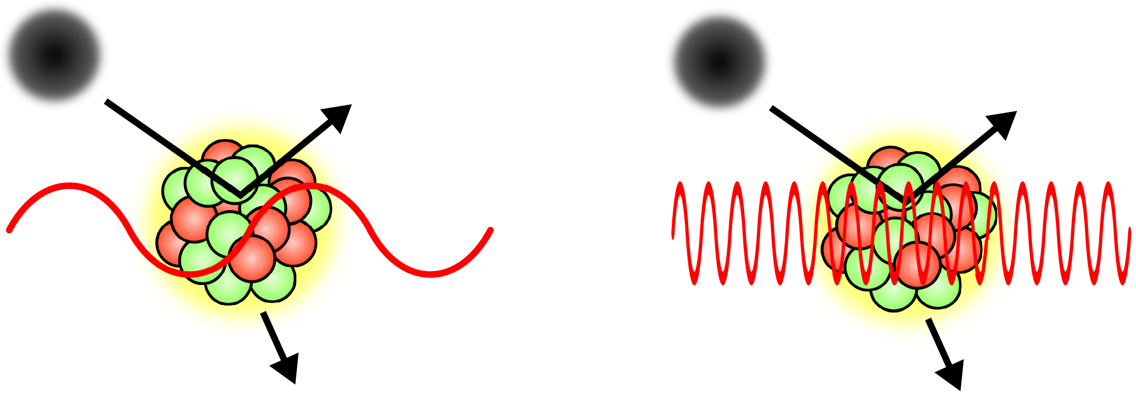
- Coherent enhancement for non-relativistic DM may be lost.
- Parametrization of incoherent scattering

$$\frac{d\sigma_{\chi N}}{dT_N} = \left(\frac{d\sigma_{\chi N}}{dT_N}\right)_{\rm coh} + \left(\frac{d\sigma_{\chi N}}{dT_N}\right)_{\rm inc} = \frac{\sigma_{\rm SI}^{\rm coh}}{T_N^{\rm max}} F_{\rm SI}^2(q^2) + \frac{\sigma_{\rm SI}^{\rm inc}}{T_N^{\rm max}} \left[1 - F_{\rm SI}^2(q^2)\right]$$

where $\sigma_{\rm SI}^{\rm coh} = \sigma_p \left(\frac{\mu_N}{\mu_p}\right)^2 \left[Z_N f_p + (A_N - Z_N) f_n\right]^2$

$$\sigma_{\rm SI}^{\rm inc} = Z_N \sigma_p + (A_N - Z_N)\,\sigma_n, \qquad F_{\rm SI}(q^2) = \left(1 + q^2/\Lambda_N^2\right)^{-1}$$

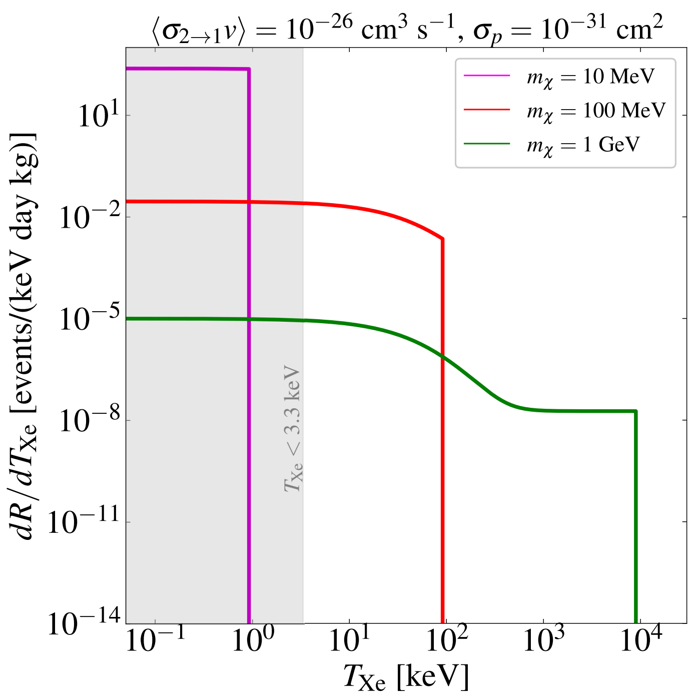
$\Rightarrow$ smooth transition between coh and inc



- Simple assumption: $f_p = f_n = 1$ and $\sigma_p = \sigma_n$

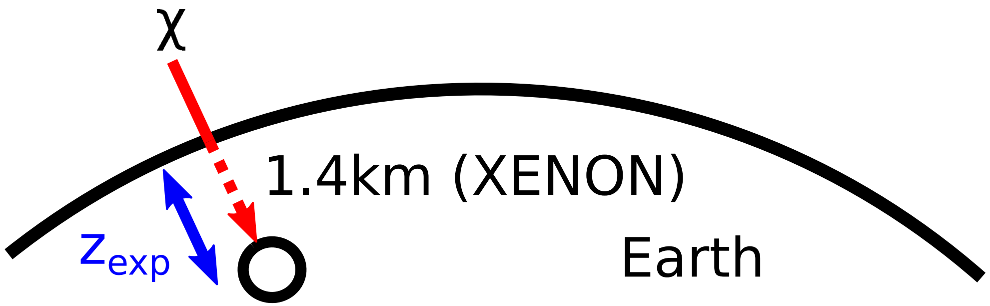
Recoil energy spectra

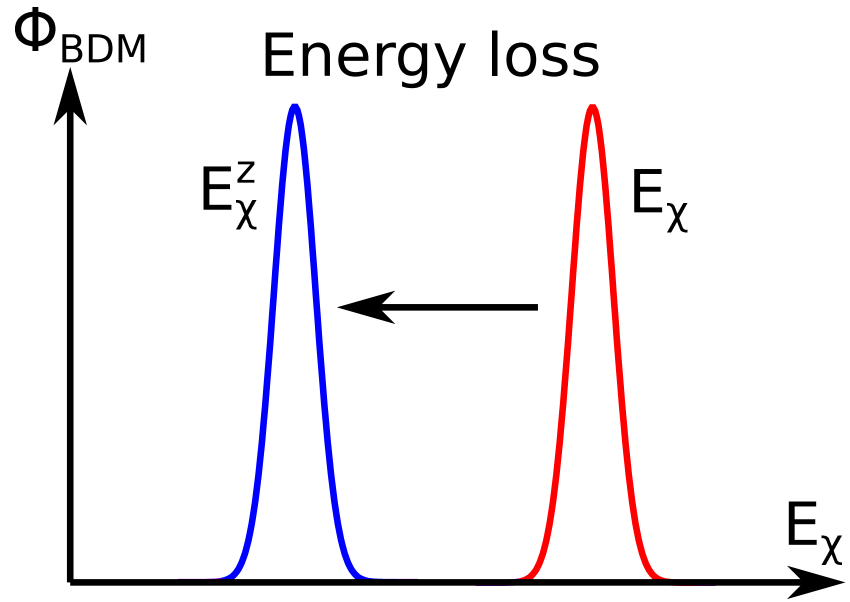
- $$\frac{dR_N}{dT_N} = \frac{1}{m_N}\int_{T_\chi^{\min}}^{\infty} \frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi} dT_\chi$$ where $$\frac{d\Phi_\chi}{dT_\chi} = \Phi_{\rm BDM}\delta\left(T_\chi - \frac{m_\chi}{4}\right)$$
  $$\Phi_{\rm BDM} \approx 3.2\times 10^{-3}\ [{\rm cm}^{-2}{\rm s}^{-1}]\left(\frac{m_\chi}{100\ {\rm MeV}}\right)^{-2}\left(\frac{\langle\sigma_{2\to1}v\rangle}{10^{-26}\ {\rm cm}^3/{\rm s}}\right)$$
- Mass threshold: $$m_\chi^{\min} = \frac{5}{4}m_N\left(\frac{9m_N}{8T^{\rm th}} - 1\right)^{-1}\left(1 + \frac{3}{5}\sqrt{1 + \frac{2m_N}{T^{\rm th}}}\right)$$
- For XENONnT, $T_{\rm Xe} =$ 3.3keV $\Rightarrow m_\chi^{\min} =$19 MeV
- $$R = \sum_N \int \frac{dR_N}{dT_N} dT_N$$ (events/kg/yr)



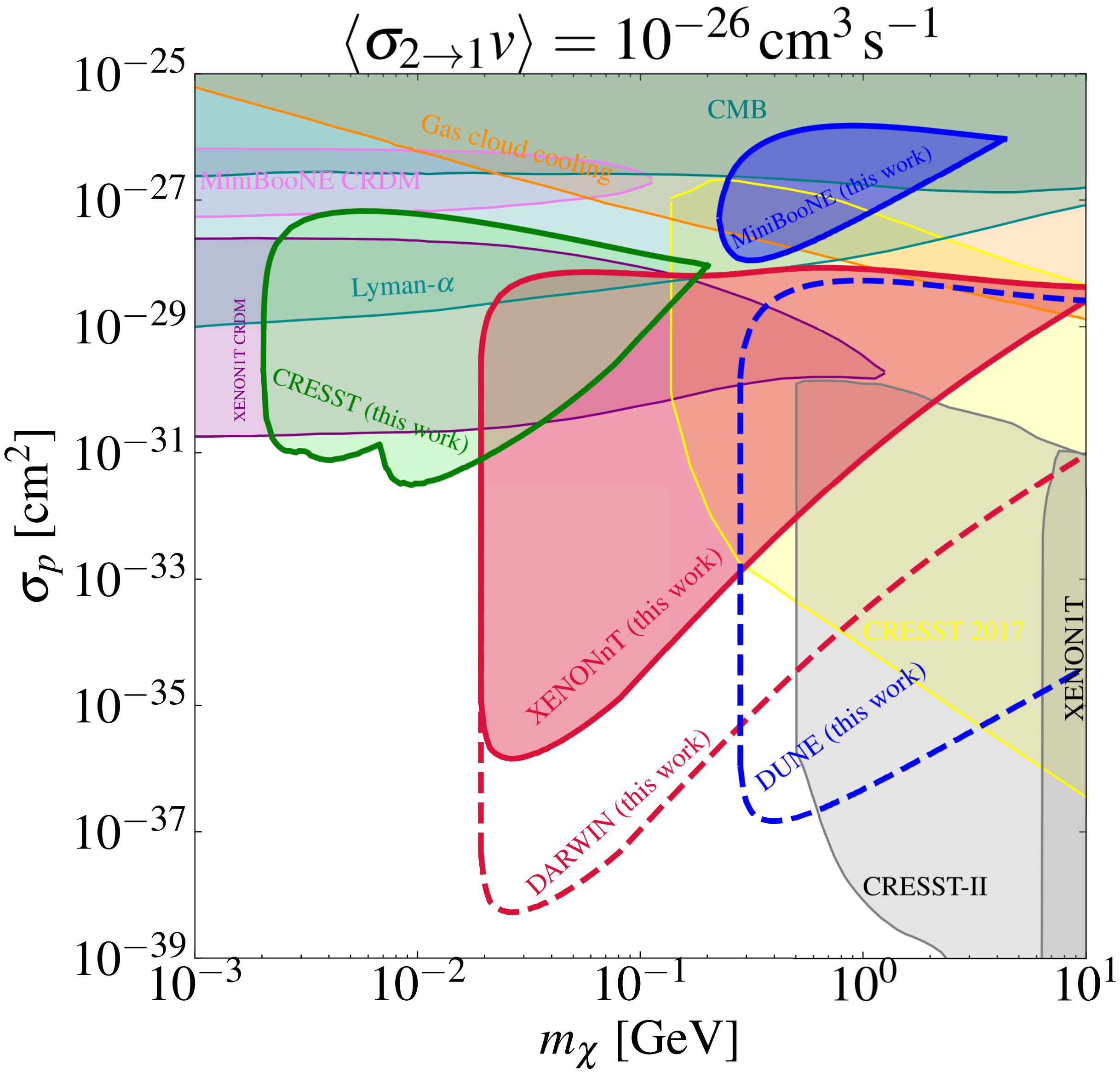
Attenuation due to overburden

- Energy loss: $\dfrac{dT_\chi^z}{dz} = -\sum_N n_N \int_0^{T_\chi^{\max}} T_\chi \dfrac{d\sigma_{\chi N}}{dT_\chi} dT_\chi$
- If $m_\chi \ll m_N$, $T_\chi(z) \approx T_\chi(0) e^{-z/\ell}$
  where $\ell \equiv \sigma_p \sum_A 2 n_N A_N^2 \left(\dfrac{m_\chi}{m_N}\right) \left(1 + \dfrac{m_\chi}{m_p}\right)^2 \left(1 + \dfrac{m_\chi}{m_N}\right)^{-4}$
- Soil component:
  O: 48%, Ca: 30%,
  C: 12%, Mg: 5.6%
  Density: $\rho = 2.71\ \mathrm{g/cm^3}$





Bound for SI cross section



- Large σ_p region is not excluded due to strong attenuation.
- The excluded region is sharply cut at a small DM mass due to experimental threshold.
- XENONnT excluded $\sigma_p \sim 10^{-35}$ [cm^2] around $m_\chi \sim$ 30 MeV
  DARWIN: $\sigma_p \sim 10^{-38}$ [cm^2]
- Coherent enhancement is lost for larger DM mass.

Summary

1. Conventional direct detection experiments have low sensitivity in sub-GeV scale.
2. Semi-annihilations accelerate DM coming from Galactic Center.
3. We found high sensitivity for BDM in sub-GeV mass range through XENON and DUNE.

Futurte work

- Apply to concrete DM models