Boosted dark matter from semi-annihilations in the galactic center

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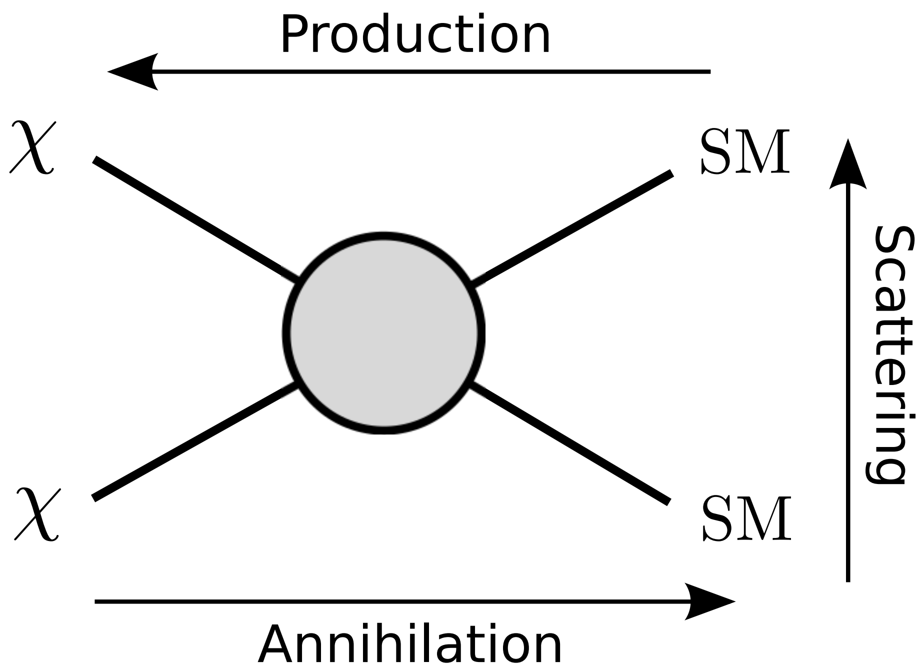
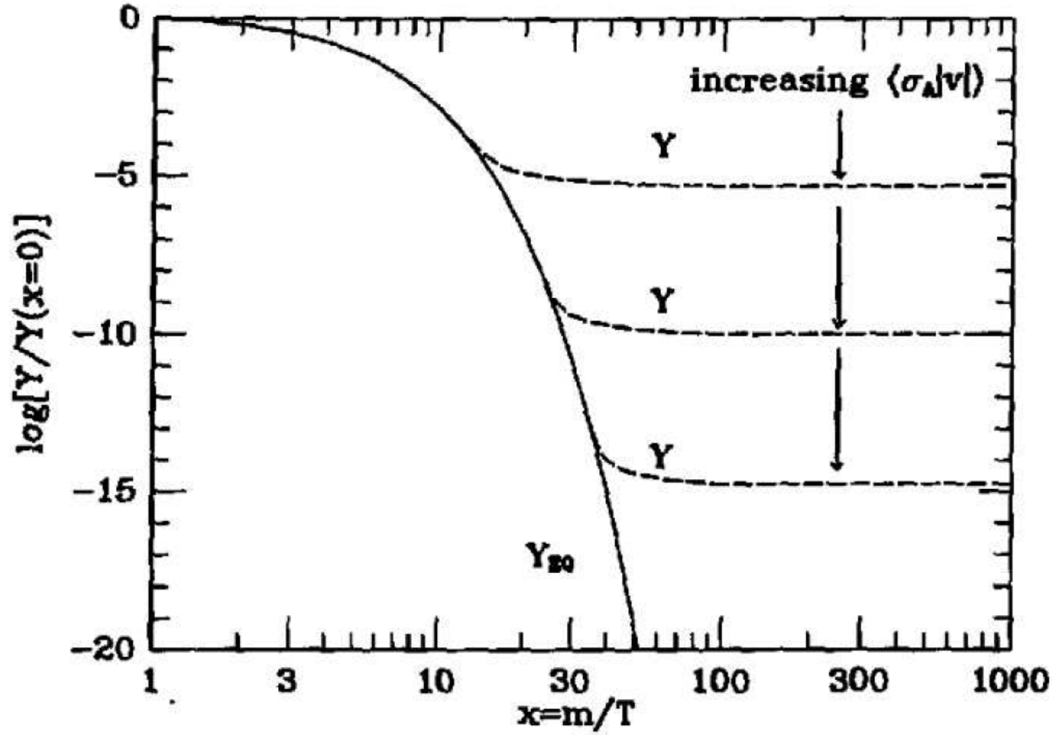
Thermal dark matter

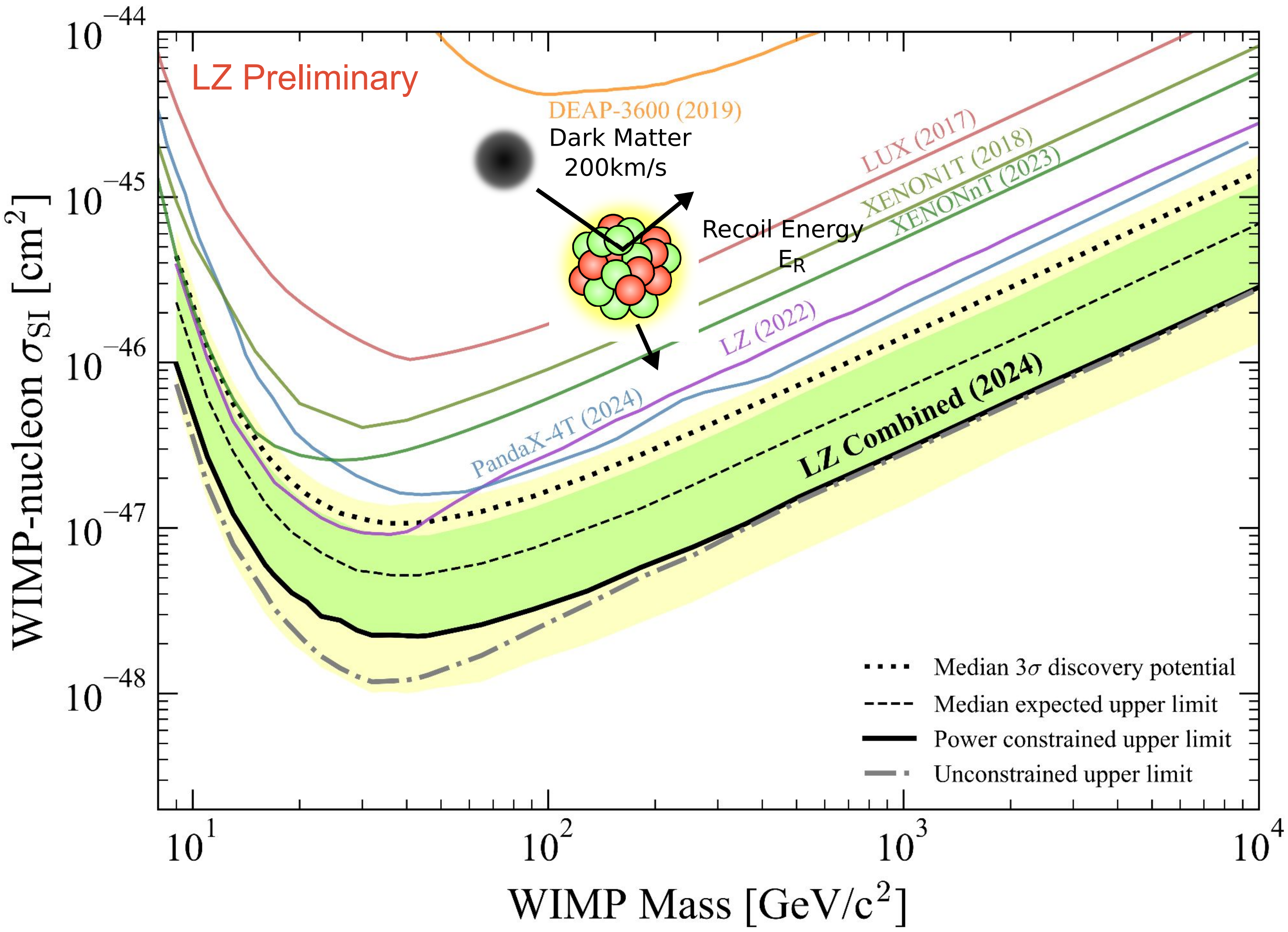


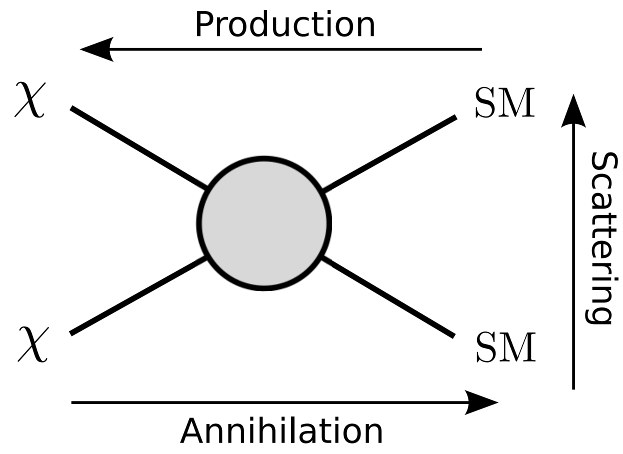


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2} \right)$$

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

Status of direct detection experiments





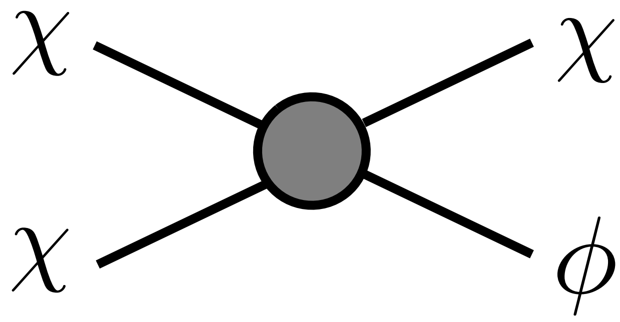
- $\Omega h^2 = 0.12$
  $\Leftrightarrow \sigma_{\rm el} \sim 10^{-36}$ cm^2
  ($\sigma_{\rm el} \lesssim 10^{-45}$ cm^2)
  (loop)

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

Non-minimal dark sector

$\mathbb{Z}_3$ symmetric DM $\Rightarrow$ cubic coupling $\mathcal{L} \supset \chi^3$



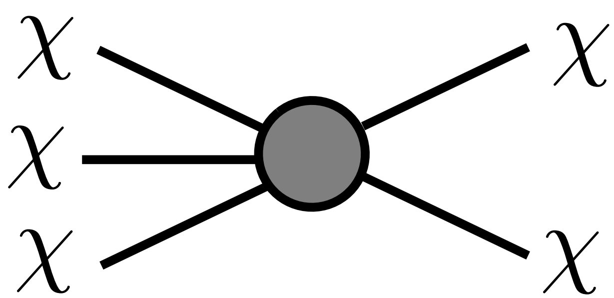
- Semi-annihilations

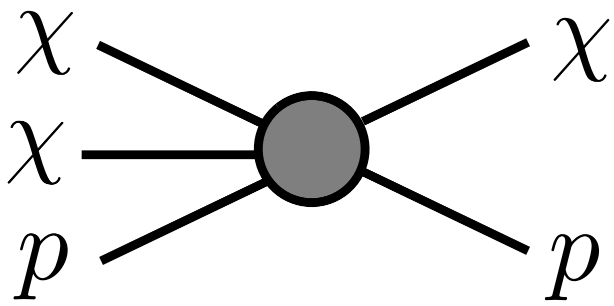
  Hambye, JHEP (2009), D'Ermao,. Thaler, JHEP (2010)

  $\chi\chi \to \overline{\chi}\phi$ $(v_\chi = \mathcal{O}(0.1 - 1))$

- SIMP, Co-SIMP Hochberg, Kuflik, Volansky, PRL (2014), Smirnov, Beacom, PRL (2020)

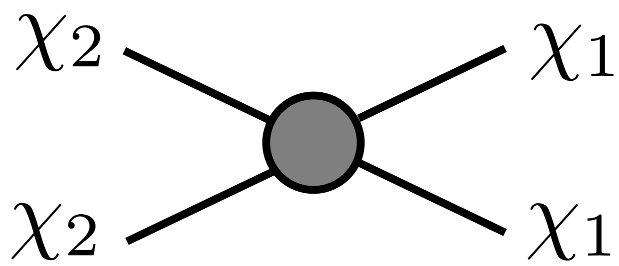
  $\chi\chi\chi \to \chi\overline{\chi}$, $\chi\chi p \to \chi p$



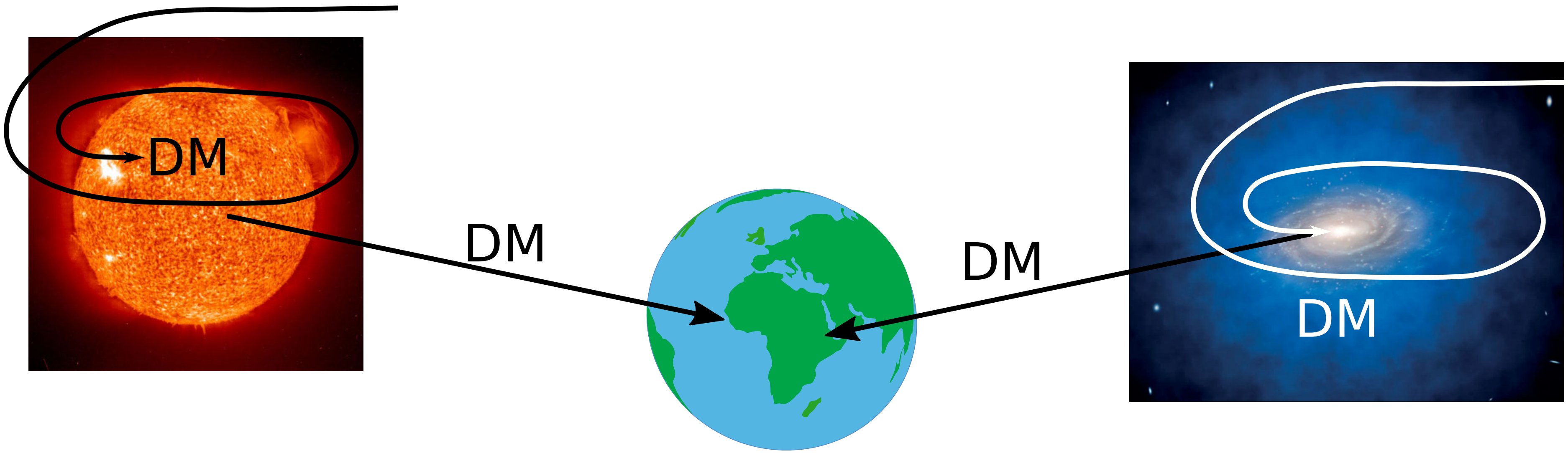


- Multi-component DM

  $\chi_2\chi_2 \to \chi_1\chi_1$



Acceleration of DM



Other acceleration mechanisms and models

- Scattering with high energy cosmic-rays — Bringmann and Pospelov, PRL (2019); Ema, Sala, Sato, PRL (2019)
- Scattering with Blazar — Wang, Granelli, Ullio, PRL (2022)
- Solar reflection — Emken, PRD (2022)
- Vacuum decay — Cline, Puel, Toma, Wang, PRD (2023), Cline, Puel, Toma, PLB (2024)

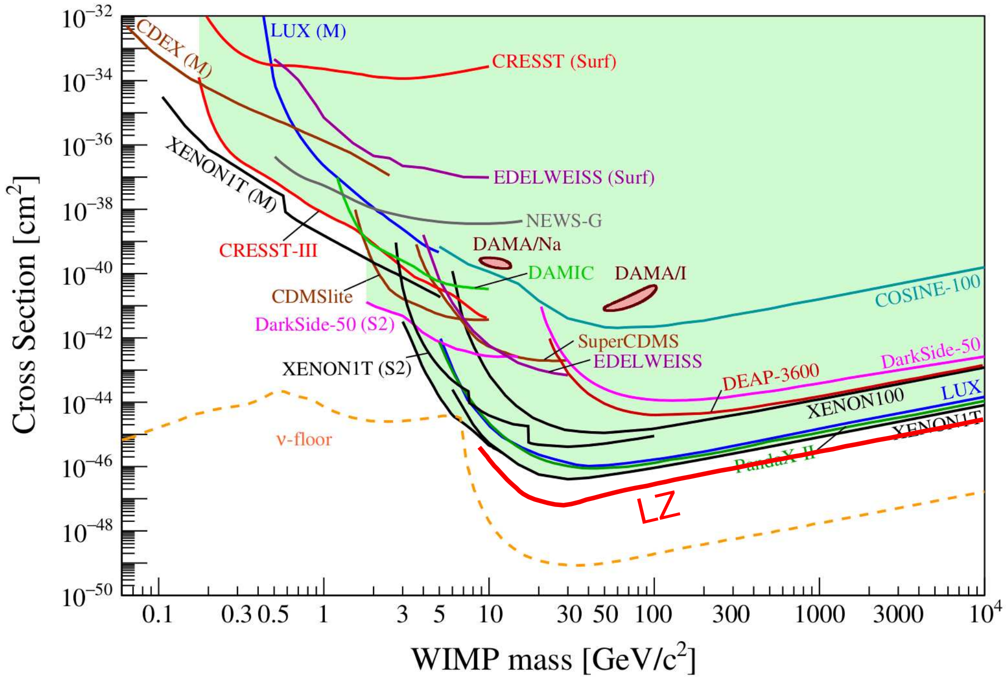
Boosted DM from semi-ann.

- We focus on $\chi\chi \to \overline{\chi}\nu \Rightarrow$ Dirac DM
  ($\chi\chi \to \overline{\chi}\phi \to \overline{\chi}f\overline{f} \Rightarrow$ indirect detection)

- DM energy in the final state: $E_\chi = \frac{5}{4}m_\chi$ (monochromatic)
  $\Rightarrow$ Moderate boost factor $\gamma_\chi \equiv \frac{E_\chi}{m_\chi} = \frac{5}{4} = 1.25 \ (v_\chi = 0.6)$

- $\gamma_\chi < \gamma^{\text{th}}_{\text{Cherenkov}} \approx 1.5$
- No deep inelastic scattering
  $\Rightarrow$ simple calculation
- Sub-GeV DM mass range can be target for semi-annihilations.

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



Scattering with nuclei

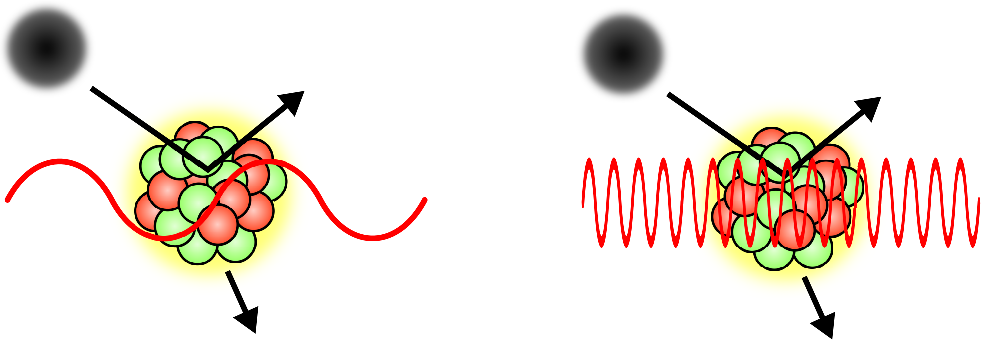
- Coherent enhancement for non-relativistic DM may be lost.
- Parametrization of incoherent scattering

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

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

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

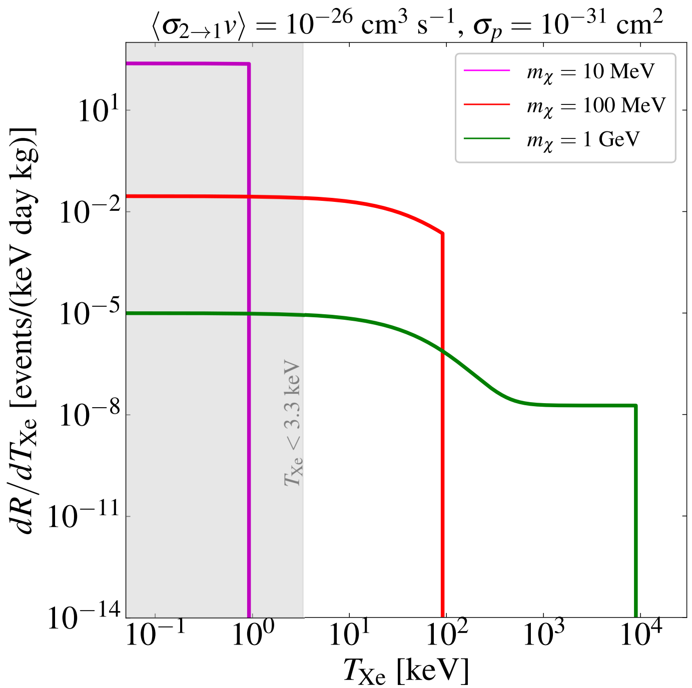
$\Rightarrow$ smooth transition between coh and inc



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

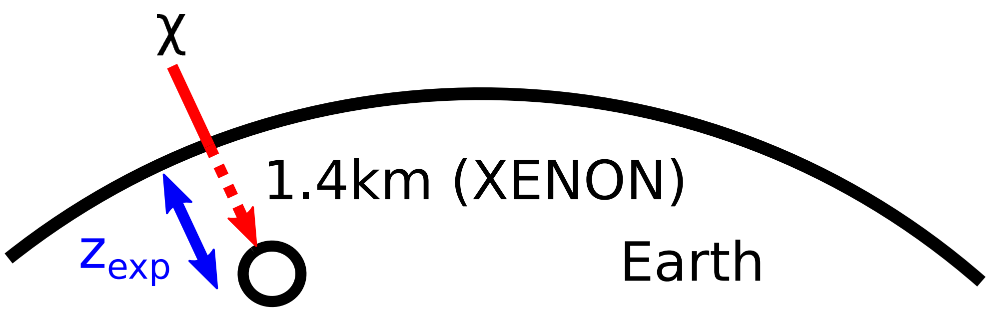
Recoil energy spectra

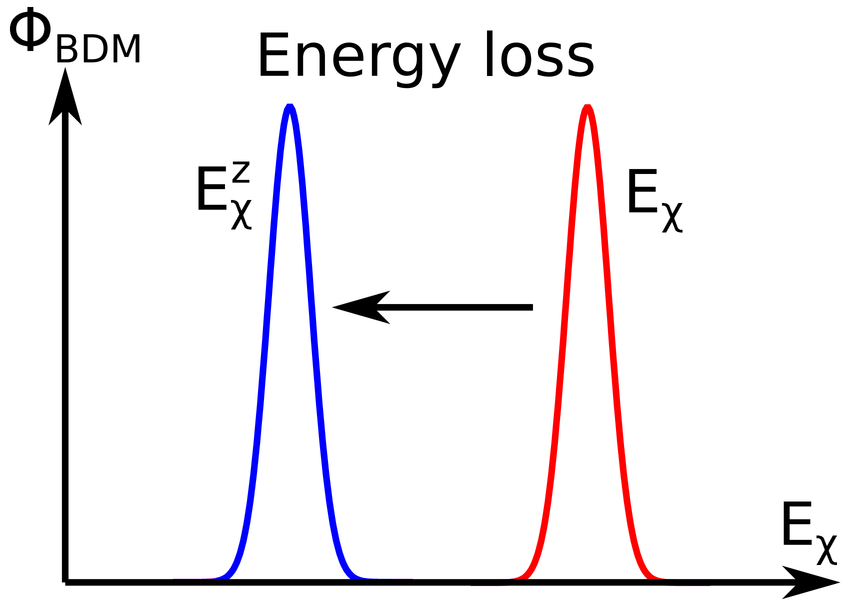
- $$\frac{dR_N}{dT_N} = \frac{1}{m_N}\int_{T_\chi^{\rm min}}^{\infty} \frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi}dT_\chi$$ where $$\frac{d\Phi_\chi}{dT_\chi} = \Phi_{\rm BDM}\delta\left(T_\chi - \frac{m_\chi}{4}\right)$$
  $$\Phi_{\rm BDM} \approx 3.2\times 10^{-3}\ [{\rm cm^{-2}s^{-1}}]\left(\frac{m_\chi}{100\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



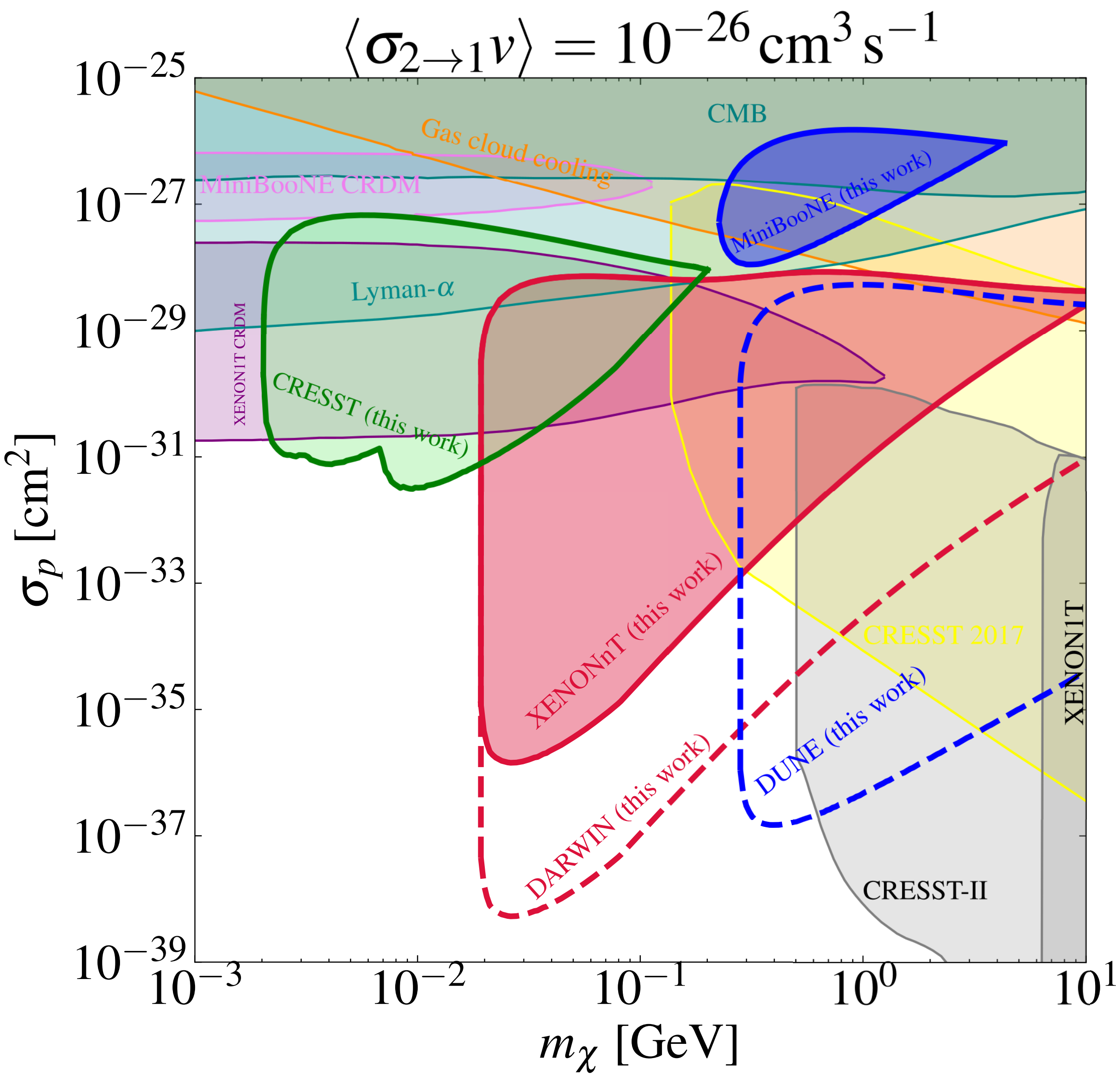
Attenuation due to overburden

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



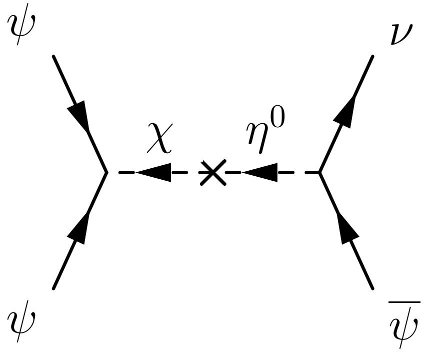


Bound for SI cross section



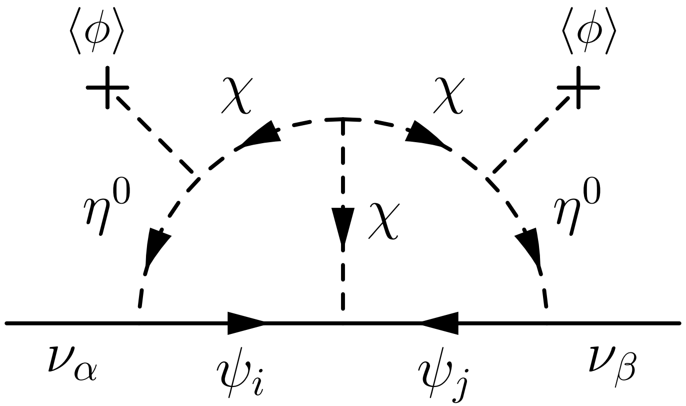
- Large σ_p region is not excluded due to strong attenuation.
- The excluded region is sharply cut at a small DM mass due to experimental threshold.
- XENONnT excluded $\sigma_p \sim 10^{-35}$ [cm^2] around $m_\chi \sim$ 30 MeV DARWIN: $\sigma_p \sim 10^{-38}$ [cm^2]
- Coherent enhancement is lost for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

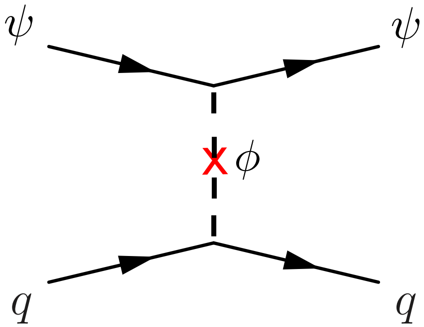
Future work



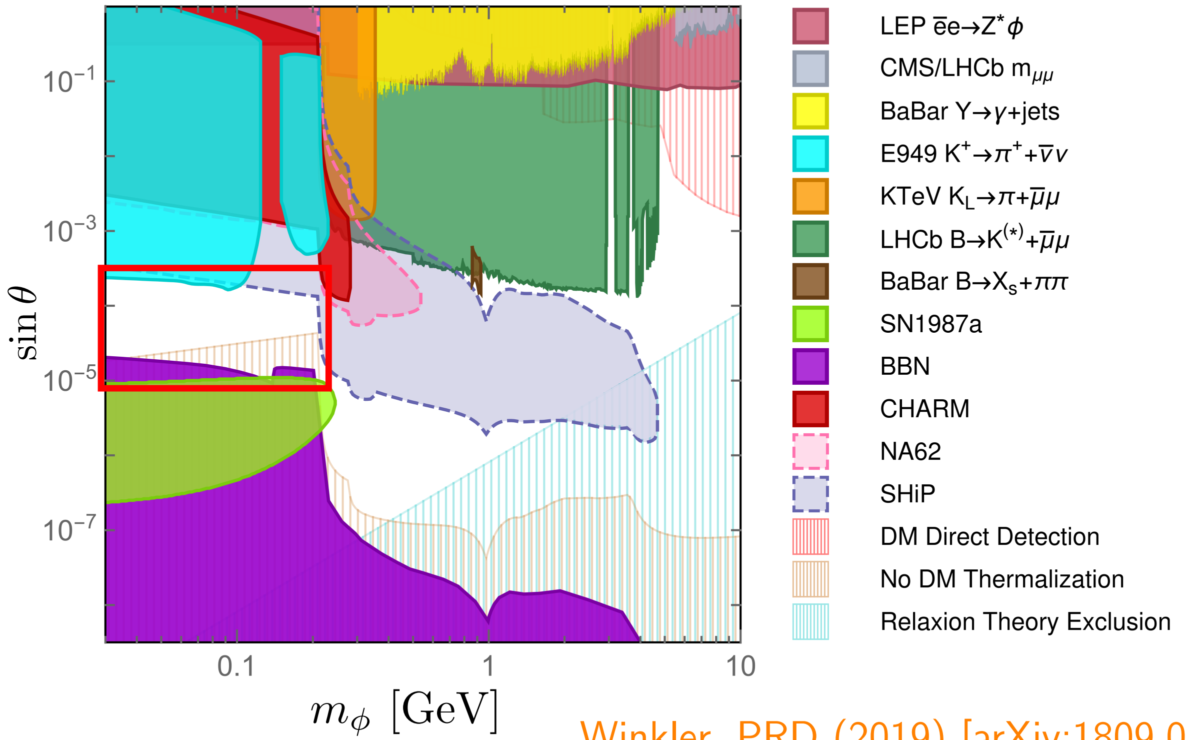
Find a concrete model

- $\mathbb{Z}_3$ symmetric neutrino mass model with a light scalar ϕ Ma, PLB 662 (2008), Aoki, TT, JCAP 09 016 (2014)
  - Scattering with nuclei through light scalar ϕ
  - Check other constraints (ν masses and mixings, LFV etc)





$\psi\overline{\psi} \to q\bar{q}$ is p-wave



Winkler, PRD (2019) [arXiv:1809.01876]

Summary

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

Futurte work

- Find a concrete DM model