Sub-GeV dark matter from cosmic ray bremsstrahlung in the atmosphere

Based on arxiv:2604.19959

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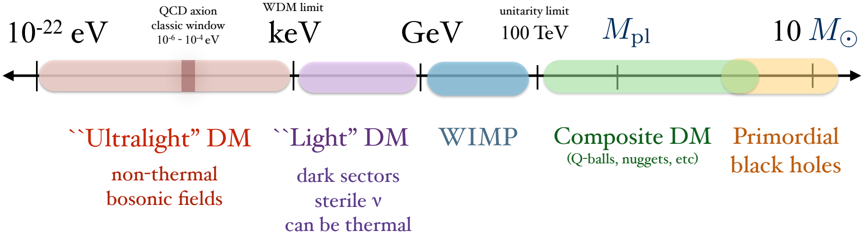
CAP Congress

June 25, 2026

University of Victoria

Mass scale of dark matter

(not to scale)



Lin (2019)

Avoiding Sub-GeV Cosmological Constraints

- We use a dark sector model with scalar candidate χ and vector V
- The dark photon interacts with SM fermions (f) as

$$\mathcal{L} \supset \epsilon e \sum_f q_f \bar{f} \gamma^\mu V_\mu f$$

- The dark sector interaction is

$$\mathcal{L} \supset i g' \chi^\dagger \partial^\mu \chi V_\mu + \text{c.c}$$

- $\langle \sigma v \rangle_{\chi\bar{\chi} \to \text{SM}} \propto v^2$ avoiding CMB constraints on Sub-GeV DM
- The free parameters in this model are m_χ, ϵ, α', and $\mathcal{R} = m_V / m_\chi$
  - We fix either $\mathcal{R} = m_V / m_\chi = 2.5$ or $m_V = 0.76\,\text{GeV}$
  - We fix $\alpha' = {g'}^2 / 4\pi = 0.1$
  - Constraints are found in the m_χ–ϵ plane

Direct Detection

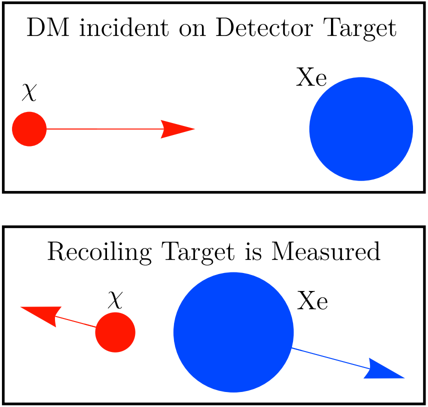
- Direct detection experiments give a scattering target for dark matter
- The number of events counted in the detector is given by

$$N = \mathcal{E} \int dT_r \eta(T_r) \int dE_\chi \frac{d\Phi_\chi}{dE_\chi} \frac{d\sigma_r}{dT_r}$$

- We use a vector-mediated elastic recoil cross-section

$$\frac{d\sigma_r}{dT_r} = \frac{m_\chi m_r}{4\mu_{\chi r}^2 T_\chi} \sigma_{\chi r} \left| F(\sqrt{2 m_r T_r}) \right|^2$$

with reference cross-section $\sigma_{\chi r}$ and the Helm Form Factor

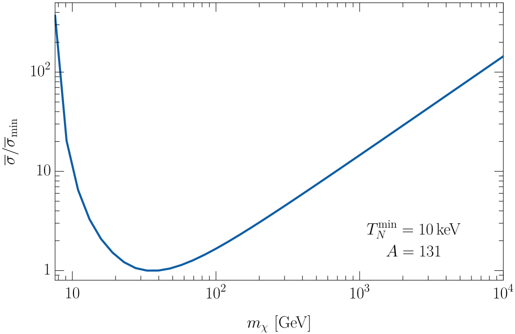


Sub-GeV Limitations on Direct Detection

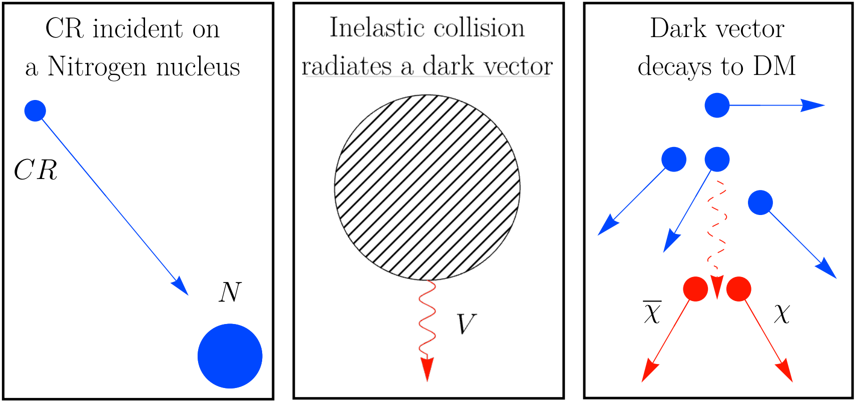
- Many direct detection experiments are optimized to find WIMP candidates in the galactic halo
- Halo candidates lose sensitivity in Xe detectors with

$$\frac{m_\chi}{0.32\,\mathrm{GeV}} \approx \left(\frac{T_N^{\mathrm{min}}}{10\,\mathrm{keV}}\right)^{1/2}$$

- Two potential solutions
  1. Lower recoil thresholds
  2. More energetic dark matter



Cosmic Ray Collisions



* More generally, the middle pane is any scattering process

** The key step in the right pane is that the dark matter candidate is produced

Cosmic Ray Production

- The flux of dark matter produced from cosmic ray collisions is

$$\frac{d^2\Phi_\chi}{dE_\chi\, d\Omega} = 2\int dE_p \frac{d^2\Phi_p}{dE_p\, d\Omega}\int dE_V \mathrm{Box}(E_\chi; E_\chi^+, E_\chi^-)\frac{1}{\sigma_{pp}^{\mathrm{tot}}}\frac{d\sigma_{\mathrm{br}}}{dE_V}$$

- The proton flux in the relevant regime follows the power law

$$\frac{d^2\Phi_p}{dE_p\, d\Omega} = \frac{1.3}{\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}\mathrm{sr}^{-1}}\left(\frac{E_p}{\mathrm{GeV}}\right)^{-2.7}$$

- The box distribution accounts for the boost into the lab frame from the vector rest frame
- The cross-section ratio is (effectively) the probability of producing a χ

Du *et al.* (2026), Du *et al.* (2024), Wu *et al.* (2024), Plestid *et al.* (2020), Argüelles *et al.* (2020), and Alvey *et al.* (2019)

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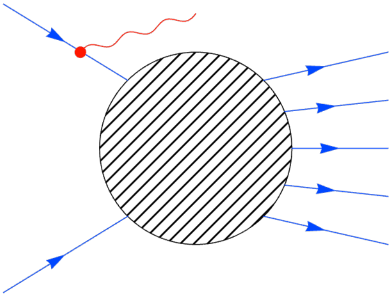
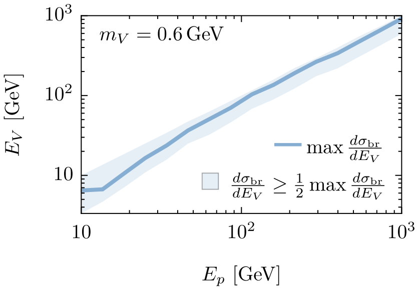
Proton Bremmstrahlung

- The production cross-section can be factorized as

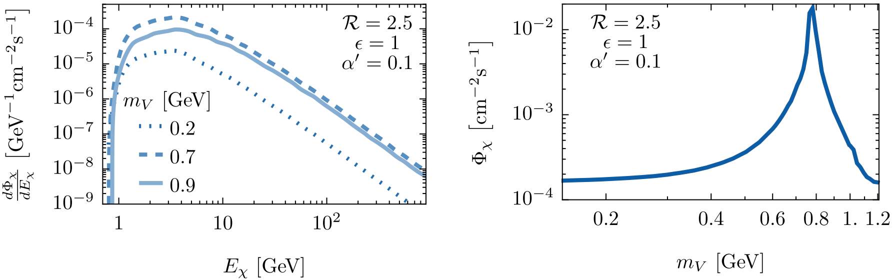
$$\frac{d^2\sigma_{br}}{dE_V\,d\theta} \approx 2\epsilon^2 p_T z \sigma_{\mathrm{NSD}}(s') w(z, p_T^2) |F_p(m_V^2)|^2 K(p_V)$$





Kling *et al.* (2026), Foroughi-Abari *et al.* (2025), Foroughi-Abari *et al.* (2022)

Producing χ



- Bremmstrahlung produces far higher energy dark matter
- The lower cutoff comes from imposing $E_p \geq 9m_p$ for consistency with the bremmstrahlung model approximations
- Total production peaks at the ρ/ω resonance
- The second peak at 1 GeV is the ϕ resonance

Aitken *et al.* (2026)

Snapshot of Results

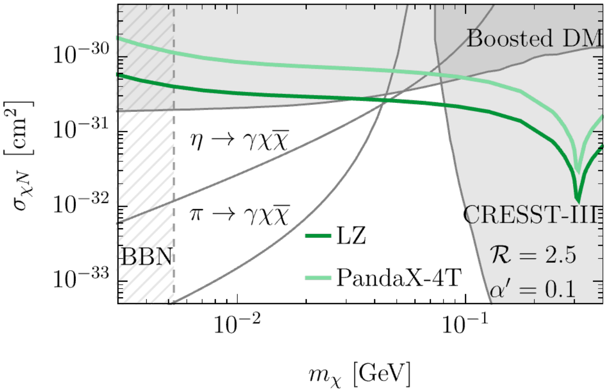
- There are 6 interesting exclusion curves arising from this work

	Nuclear Recoil	Electron Recoil	Accelerator
Fixed $\mathcal{R}$	✓	×	×
Fixed m_V	✓	✓	×

- Recall that $\mathcal{R} \equiv m_V/m_\chi = 2.5$ for fixed $\mathcal{R}$
- Recall $m_V = 0.76\,\mathrm{GeV}$ for fixed m_V
- The fixed m_V accelerator plot is not enlightening
- Nuclear recoil bounds use DM direct detectors
- Electron recoil bounds use neutrino detectors

Fixed $\mathcal{R}$ using Nuclear Scattering

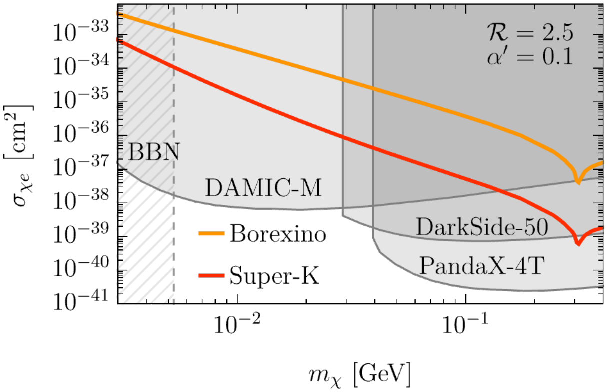
- Rare meson decays dominate in the lower mass regime
- Rare meson decays and bremsstrahlung could be combined (with care) as inelastic CR production



CRESST (2024), Alvey *et al.* (2019), Bringmann and Pospelov (2019)

Fixed $\mathcal{R}$ using Electron Scattering

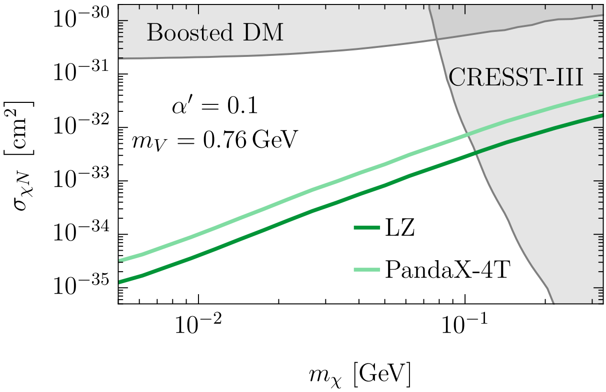
- Dedicated sub-GeV searches dominate in the electron scattering regime



DAMIC-M (2025), DarkSide (2023), PandaX (2023)

Fixed m_V using Nuclear Scattering

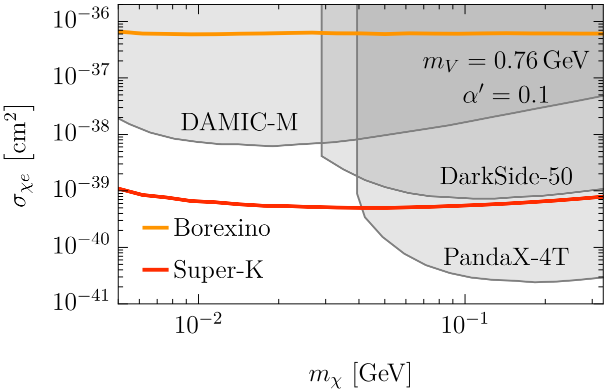
- Using the ρ/ω resonance is ideal for our model
- The heavy mediator suppresses meson decays (off the plot)



CRESST (2024), Bringmann and Pospelov (2019)

Fixed m_V with Electron Scattering

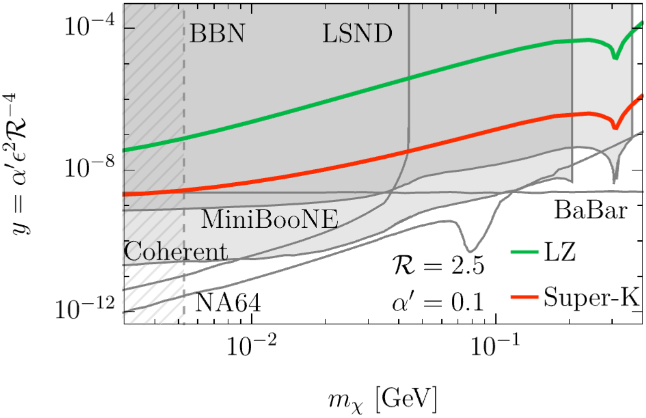
- The high thresholds of Super-K allow it to probe the very energetic DM signal at low m_χ



DAMIC-M (2025), DarkSide (2023), PandaX (2023)

Accelerator Bounds

- These limits are far stronger than what we recover even at the resonant peak
- Unfilled limits are dependent on a leptonic coupling



NA64 (2024), COHERENT (2023), MiniBooNE (2018), BaBar (2017), deNiverville *et al.* (2011), LSND (2001)

Summary

- Direct detection experiments using nuclear scattering are optimized to detect WIMPs with $m_\chi \gtrsim 1\,\mathrm{GeV}$
- Boosted dark matter can overcome recoil thresholds to produce signal in nuclear scattering detectors and even neutrino detectors
- Dark vectors produced via bremmstrahlung in the atmosphere produces a boosted DM energy spectrum
- The limits found using this method probe some new parameter space compared to current direct detection searches

Future Outlook

- Bounds will only get stronger with increased exposure and next generation detectors
- The scattering code is very flexible for input from other models
- Bremsstrahlung production is currently being studied for other (similar) mediators and candidates

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Thank You!

Backup - Boost Integral

- We define

$$E_\chi^\pm = \gamma(E'_\chi \pm \beta p'_\chi)$$

where the primed coordinates are in the vector rest frame

- We have the relation that $E'_\chi = m_V/2$ and $p'_\chi = \sqrt{m_V^2/4 - m_\chi^2}$
- The box distribution is defined as

$$\text{Box}\left(E_\chi; E_\chi^+, E_\chi^-\right) = \frac{\Theta\left(E_\chi - E_\chi^-\right)\Theta(E_\chi^+ - E_\chi)}{E_\chi^+ - E_\chi^-}$$

i.e. a uniform probability of $1/(E_\chi^+ - E_\chi^-)$ between E_χ^- and E_χ^+.

- The paper uses an alternative method where instead we solve for $E_\chi = E_\chi^\pm(E_V)$ then directly apply bounds to the E_V integral

Backup - Scattering Details

- The reference cross-section is defined as

$$\sigma_{\chi r} = 16\pi\alpha\alpha'\epsilon^2 \frac{\mu_{\chi r}^2}{m_V^4}$$

- We use the suitably normalized Helm form factor

$$|F(Q)|^2 = Z^2 \left(\frac{\mu_{p\chi}}{\mu_{N\chi}}\right)^2 \left(\frac{3j_1(R_1 Q)}{R_1 Q}\right)^2 \exp(-Q^2 s^2)$$

for nuclear scattering

Backup - Bound Statistics

- We calculate an ϵ bound with

$$\epsilon^4 = \frac{N_{\text{cl}}}{N(m_\chi, m_V, 1)}$$

since both the flux and cross-section are proportional to ϵ^2

- The event number threshold is given by

$$N_{\text{cl}} = \frac{2}{\sqrt{\pi \sigma_{\text{bkg}}^2}} \left[1 + \text{erf}\left(\frac{N_{\text{bkg}}}{\sqrt{2\sigma_{\text{bkg}}^2}} \right) \right]^{-1}$$

where $\sigma_{\text{bkg}} = 1 - C.L.$ and N_{bkg} is given by the experiment

Backup - Bremsstrahlung Details

- The non-single diffractive cross-section is

$$\sigma_{\mathrm{NSD}} = \sigma_{pp\to X} = 1.76 + 19.8 \left(\frac{s}{\mathrm{GeV}^2}\right)^{0.057} \mathrm{mb}$$

  where X is any final state that doesn't include the initial protons
- The other definition is $\sigma_{\mathrm{NSD}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{SD}}$
- The splitting function, $w(z, p_T^2)$, is a kinematic function
- $F_p(m_V^2)$ is a form factor accounting for proton structure
  - This is main source of the structure
  - It is a weighted sum of Breit-Wigner functions fit to data
- $K(p_V)$ is a form factor accounting kinematic constraints

Kling *et al.* (2026), Foroughi-Abari *et al.* (2025), Likhoded *et al.* (2010)

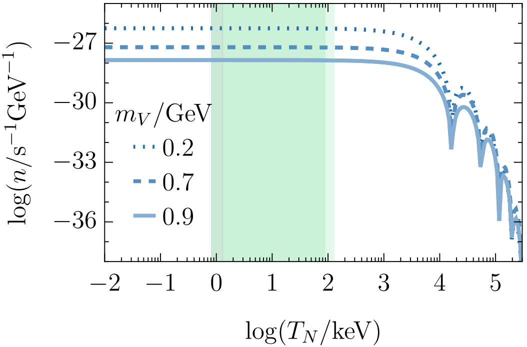
Backup - Optimizing Recoil Ranges - Nuclear

- The event spectrum

$$n = \int dE_\chi \frac{d\Phi_\chi}{dE_\chi} \frac{d\sigma_r}{dT_r}$$

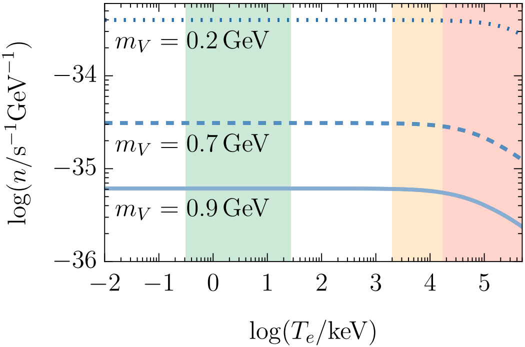
shows the region of optimal sensitivity

- Detectors:
  - LZ (dark)
  - PandaX-4T (light)
  - Both (medium)
- Free parameters:
  - $\mathcal{R} = 2.5$
  - $\epsilon^2 \alpha' = 0.1$



Backup - Optimizing Recoil Ranges - Electron

- The high energy event spectrum makes elastic collisions in neutrino detectors viable
- Detectors:
  - LZ (Green)
  - Borexino (Yellow)
  - Super-K (Red)
- Free parameters:
  - $\mathcal{R} = 2.5$
  - $\epsilon^2 \alpha' = 0.1$



Aitken *et al.* (2026), Borexino (2020), LZ (2020), Super-K (2018)