Impact of Dark Parton Shower and DM PDFs on Cosmic Ray Boosted DM

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Outline

01 **Cosmic-Ray Boosted Dark Matter**

Baseline CRDM flux from cosmic-electron upscattering.

02 **Dark Parton Shower in DM–Cosmic-Electron Scattering**

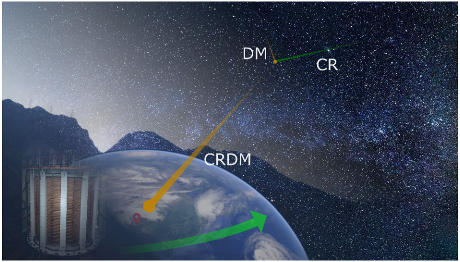
FSR reshapes the CRDM flux, then modifies recoil rates and exclusion limits.

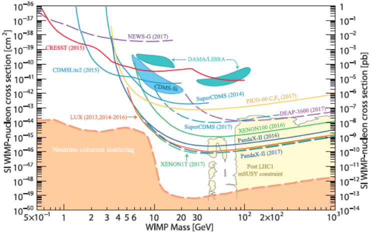
03 **DM PDF Effects in DM–Electron Scattering at Super-K/JUNO**

DM PDFs encode initial-state radiation, then modify recoil rates and exclusion limits.

Cosmic-Ray Boosted Dark Matter

Cosmic-Electron Acceleration of Dark Matter





Basic idea

- Current direct detection has limited sensitivity to light, low-speed halo DM.
- Cosmic electrons can boost halo DM to be energetic.
- Light DM can then produce above-threshold recoil signals at detectors.

Model and CRDM Flux Assumptions

CRDM Flux Formulation

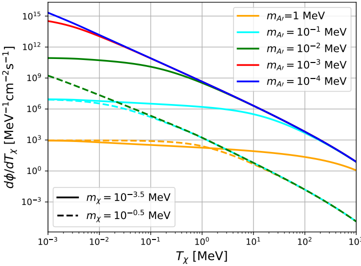
$$\frac{d\Phi_\chi}{dT_\chi} \simeq D_{\rm eff}\,\frac{\rho_\chi^{\rm local}}{m_\chi}\int_{T_{\rm CR}^{\rm min}}^{\infty} dT_{\rm CR}\,\frac{d\Phi_e^{\rm LIS}}{dT_{\rm CR}}\,\frac{d\sigma_{\chi e}}{dT_\chi}$$

Simplified Electron-Philic Dark Photon Model

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu\chi + \epsilon g_{\rm em} A'_\mu \bar{e}\gamma^\mu e$$

- CR-electron distribution is approximated as homogeneous, the local LIS is used.
- Effective distance $D_{\rm eff} \simeq 8.02\ {\rm kpc}$ encodes the spatial effects over the 10 ${\rm kpc}$ line-of-sight.

CRDM flux and $m_{A'}$ dependence



CRDM fluxes ($\epsilon = 1$, $g_D = 1$).

Mass sensitivities:

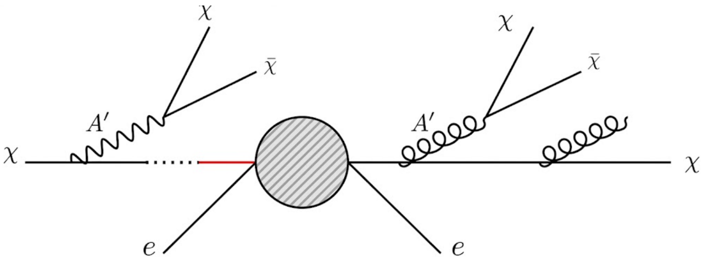
- **Low** T_χ: Fluxes are strongly suppressed by $m_{A'}$ ($\propto m_{A'}^{-4}$).
- **High** T_χ: Weaker dependence.

- **Lighter** A': Yields a rapidly falling CRDM flux.
- **Heavier** A': Yields a flatter spectrum with a more significant high-energy component.

Dark Parton Shower in DM–Cosmic-Electron Scattering

Dark Parton Shower in DM–cosmic electron scattering

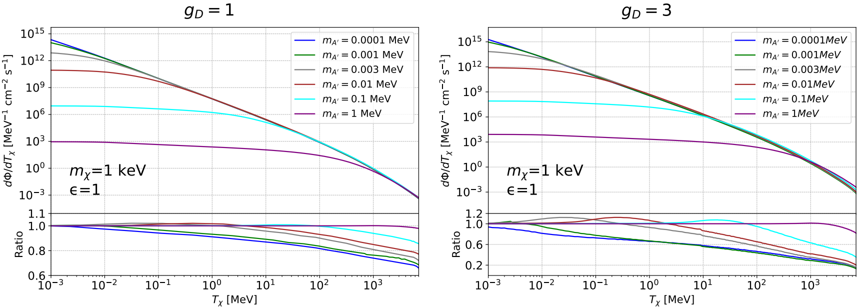
Cosmic-electron DM scattering: when Q, $E_\chi \gg m_{\chi,A'}$, final-state dark parton showering should be included.



Dark parton shower after CR upscattering.

- In baseline CRDM, one keeps the primary upscattering $e + \chi \to e + \chi$.
- The shower produces multiple dark-sector particles and softens the leading χ.

Impact of Dark Parton Showering on the CRDM Flux



CRDM flux with dark parton showering ($m_\chi = 1\ \mathrm{keV}, \epsilon = 1$).

- For heavier A', a mild enhancement may appear at low T_χ.
- For lighter A', the suppression at high T_χ is more significant.

Ratio $\equiv$ with dark parton showering / without showering (baseline).

How Dark Parton Showering Reshapes the CRDM Flux

At fixed T_χ, dark parton showering reshapes the CRDM flux through two competing effects:

Loss Term

DM particles originally at T_χ lose energy through parton shower, reducing the flux in the T_χ bin.

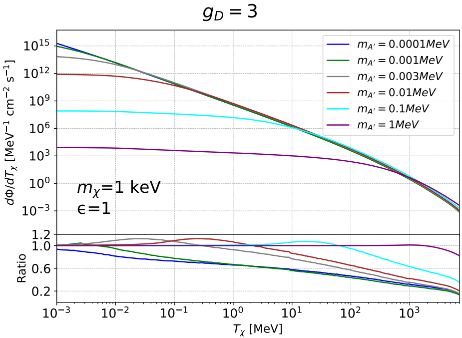
Gain Term

More energetic DM particles can produce DM with T_χ through parton shower, increasing the flux in the T_χ bin.

Net Effect

- Dark showering **enhances** the CRDM flux if the pre-showering spectrum is flat (heavy A' case).
- Dark showering **suppresses** the CRDM flux if the pre-showering spectrum is steeply falling (light A' case).

Experimental Windows on Dark Parton Showering Effects



PandaX / XENON

- $T_R \sim \mathcal{O}(10)\,\mathrm{keV}$
- Low T_χ; mild enhancement possible

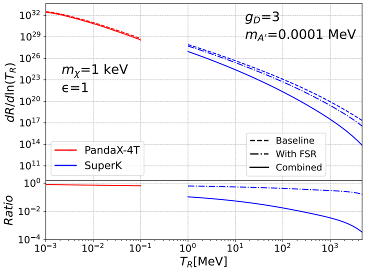
JUNO

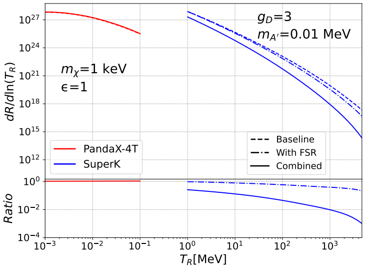
- $T_R \sim \mathcal{O}(10)\,\mathrm{MeV}$
- High T_χ; visible dark parton showering suppression

Super-K

- $T_R > 100\,\mathrm{MeV}$
- High T_χ tail; strongest dark parton showering suppression

Impact of Dark Showering on Recoil Rates





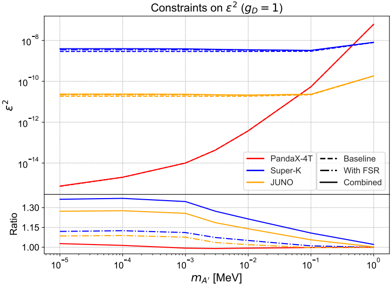
Ratio $\equiv$ with dark parton showering / baseline (without showering)

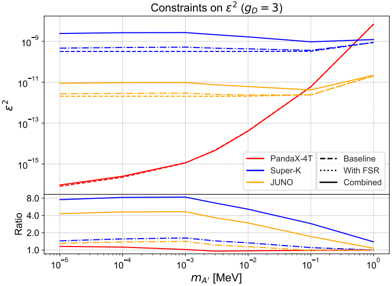
$g_D = 3$ (1)

$m_{A'}$	**PandaX** 10 keV	**JUNO** 10 MeV	**Super-K** 100 MeV
10^{-4} MeV	0.72 (0.95)	0.54 (0.85)	0.43 (0.80)
10^{-2} MeV	1.08 (1.02)	0.80 (0.97)	0.59 (0.92)

At large T_χ, recoil rates are suppressed; only a mild low-energy enhancement appears for heavier A'.

Impact of dark parton showering on Exclusion Limits





- PandaX-4T is more sensitive to lighter A', while JUNO and Super-K are more sensitive to heavier A'.
- Dark parton showering mainly relaxes the exclusion limits; it only slightly strengthens the PandaX-4T limit for heavier A'.

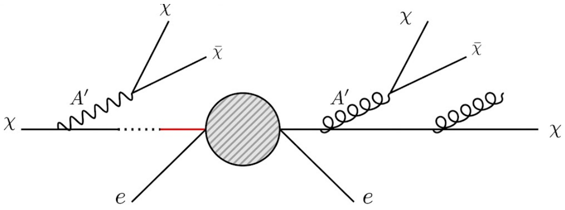
Ratio $\equiv$ with dark parton showering / without showering (baseline).

Largest impact: $m_{A'} \simeq 10^{-3}\,\mathrm{MeV}$ and $g_D = 3$.
ϵ^2 exclusion-limit ratio: 1.6 (Super-K), 1.4 (JUNO).

DM PDF Effects in DM–Electron Scattering at Super-K/JUNO

Initial State Radiation and the DM PDF Picture

At JUNO and Super-K, Q, $E_\chi \gg m_{\chi,A'}$, so ISR should be included.



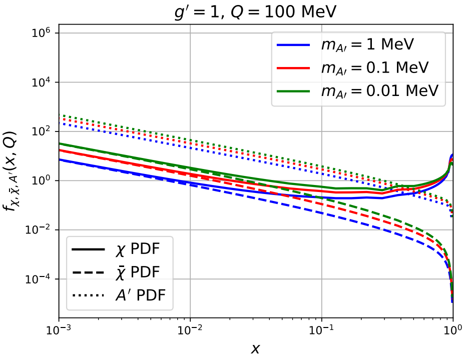
Scattering at detector

Key point: the red incoming leg can be χ, $\bar{\chi}$, or A' carrying a fraction x of the incident CRDM momentum.

$$\sigma(\chi + e^- \to \cdots) = \sum_{i=\chi,\bar{\chi},A'} \int_0^1 dx\, f_i(x, Q)\, \sigma(i + e^- \to \cdots)$$

- Collinear splitting effects are encoded in the DM PDFs.
- Following the factorization theorem, cross sections require summing over χ, $\bar{\chi}$, and A' components with their respective PDFs.

DM PDF Results



DGLAP evolution

$$\frac{df_i(Q,x)}{d\ln Q^2} = \sum_{m,n} N \int_x^1 \frac{dz}{z} P_{m\to i+n}(z) f_m\left(Q, \frac{x}{z}\right) - \sum_{j,k} \int_0^1 dz\, P_{i\to j+k}(z) f_i(Q,x)$$

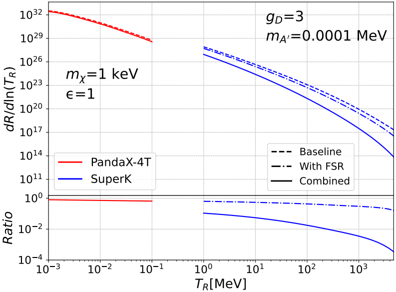
Initial condition

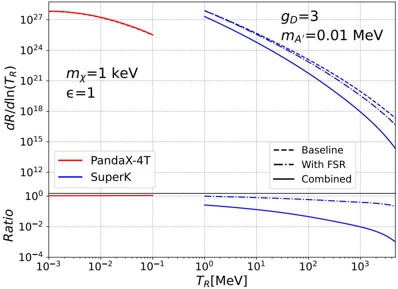
$$Q_0 = \max(m_{A'}, m_\chi)$$

$$f_i(Q_0,x) = \begin{cases} \delta(1-x), & i = \chi \\ 0, & i \neq \chi \end{cases}$$

- Starting from $f_\chi(Q_0,x) = \delta(1-x)$, evolution softens the χ distribution while it is still primarily concentrated near $x = 1$.
- The A' component mainly appears in the low-energy(small-x) region.

Combined Effects on Recoil Rates

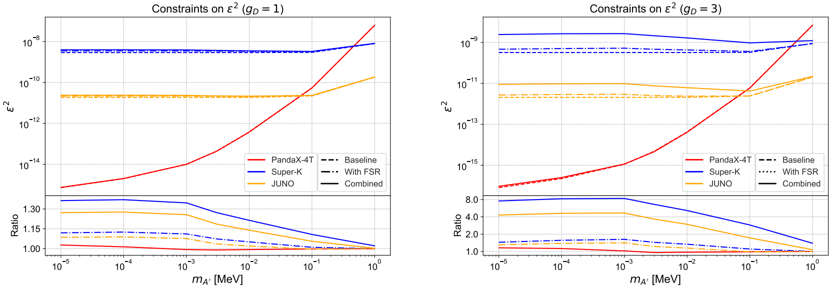




Combined $\equiv$ Dark parton shower + DM PDF corrections;
only Super-K/JUNO.

- DM PDF effects further suppress the electron recoil spectra.
- The χ component is softened, while the $\bar{\chi}/A'$ components are mainly low-energy and cannot efficiently pass the recoil threshold.

Combined Effects on Experimental Exclusion Limits



Combined $\equiv$ Dark parton shower + DM PDF corrections; only Super-K/JUNO.

- DM PDFs further relax the Super-K/JUNO exclusion limits, compared with parton shower alone.

Summary

- Cosmic electrons can boost halo DM to be energetic, then produce above-threshold recoil signals at detectors.
- **Acceleration stage:** Dark parton showering mainly suppresses the CRDM flux, especially toward the high-T_χ tail.
- **Detection stage:** Dark parton showering and DM PDF together suppress the recoil signal, especially at Super-K/JUNO.

Take-home message: Dark parton showering and DM PDF effects are essential for interpreting high-energy CRDM searches.


Thank
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