Light Dark Matter from Inelastic Cosmic Ray Collisions

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based on arXiv:1905.05776
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Warsaw, Poland

Beyond GR and the Cosmological SM, July 2019.
The Unexplored Parameter Space.

Motivation

The problem with low mass DM → DD experiments are not sensitive to them.
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New Ideas using CRs

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New Ideas using CRs

- If CRs interact with SIDM, elastic scattering can modify the spectrum of detected CRs on Earth: Reverse Direct Detection.
- In the same interaction, momentum is transferred to the DM particles, that receive a boost, increasing the sensitivity of DD: Elastic CRDM.

The Process.

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In CRs pions are produced 10 times more often than eta-mesons, but its branching ratio into invisible is \(10 \sim 100\) times more constrained.
The Simulation.

We simulate the collisions with nitrogen in the atmosphere using the CRMC package† and describe the effect of the atmosphere as

$$\frac{d\Phi_p}{dT_p}(T_p, h) \equiv Y(h) \frac{d\Phi_p}{dT_p}(T_p).$$

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†by R. Ulrich et al, https://github.com/alisw/crmc
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The Flux.

We can obtain the dark matter flux as measured by a detector on Earth (at depth $z_d$) as

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{d\Phi_p}{dT_p} n_0^0 H_{\text{eff}} \sigma_{pN \rightarrow M} B R_{M \rightarrow \chi\chi}$$
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with

$$n^0_N \equiv 5 \times 10^{19} \text{ cm}^{-3},$$

$$H_{\text{eff}} \equiv \int_{R_E}^{R_E+h} R^2 dR \int_0^{2\pi} d\phi \int_{\cos \theta_{\text{max}}}^1 \frac{d(cos\theta)}{2\pi l(R, \theta, z_d)^2} \times y(R-R_E)$$
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The Earth’s Attenuation.

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\[ T_\chi^0 = \frac{2m_\chi T^z_\chi e^{l_E/L}}{2m_\chi + T^z_\chi (1 - e^{l_E/L})} \]

with the mean free path length given by

\[ L \equiv \left( \sum_N n_N \sigma_{\chi N} \frac{2m_N m_\chi}{(m_\chi + m_N)^2} \right)^{-1} \]
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The Rate.

The expected rate coming from the ICRDM contribution at a detector is given by

\[ \Gamma_N = N_T \int_{T_1}^{T_2} dT_N \int_{T_{\chi}^{\text{min}}(T_N)}^{\infty} dT_\chi \epsilon(T_N) \frac{d\Phi_\chi}{dT_\chi} \frac{d\sigma_{\chi N}}{dT_N}, \]

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Taken from [Phys. Rev. Lett. 121, 111302 (2018)]
(Current) Experiment: XENON1T

**Characteristics**
- $T = 278.8$ live days.
- $M = 1300 \pm 10$ kg fiducial mass.
- $E = [4.9, 40.9]$ keV$_{nr}$.
- $N(90\% \text{ C.L.}) = 3.56$

Data from [Phys. Rev. Lett. 121, 111302 (2018)]
**Characteristics**

- $T = 1000$ live days.
- $M = 5600$ kg fiducial mass.
- $E = [4.9, 40.9]$ keV$_{nr}$.
- $N(90\% \text{ C.L.}) = 3.56$.

Data from [arXiv:1802.06039 [astro-ph.IM]]
The Limits.

\[ \sigma_X [\text{cm}^2] \]

- \( m_\chi = 1 \text{ MeV} \)
- \( m_{\text{med}} = 10 \text{ MeV} \)

- Elastic CRDM
- Inelastic CRDM (\( \eta \))
- Inelastic CRDM (\( \pi \))

\[ \text{BR}(M \rightarrow M'\chi\chi) \]

Motivation  The Idea  The Results  Conclusions
The Limits.
A Particular Model.

If we consider a hadrophilic scalar mediator model\(^\ddagger\)

\[ \mathcal{L} \supset -g_{\chi} S \bar{\chi} L \chi_R - g_u S \bar{u}_L u_R + \text{h.c.}, \]

we end up with four free parameters: \(m_{\chi}, m_S, g_{\chi}\) and \(g_u\).

\(^\ddagger\)Batell et al, arXiv:1812.05103
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- A particular model has been presented, in which XENON1T presents competitive limits, comparable to those coming from dedicated experiments like MiniBooNE.
Conclusions.

- The possibility of extending the sensitivity of direct detection experiments to low dark matter masses using a cosmic beam dump-like effect has been explored.
- A particular model has been presented, in which XENON1T presents competitive limits, comparable to those coming from dedicated experiments like MiniBooNE.
- In the future we intend to explore other hidden sectors, independently of dark matter, using similar methods.
Thank you!
Backup Slides: Other Limits

![Graph showing limits on spin-independent WIMP-nucleon cross-section](image)

Extracted from [Phys. Rev. D97, 103530 (2018)]
Backup Slides: Other Limits

![Graph showing limits with m_x (GeV) on the x-axis and \( \sigma_{nx} \) (cm\(^2\)) on the y-axis. Key features include XQC, SAPPHIRE, gas cloud cooling, and CMB scattering.]

Extracted from [Phys. Rev. Lett. 121, 131101 (2018)]
Backup Slides: Other Limits

![Graph showing constraints on dark matter mass and cross section.](image)

**The ISM vs The Atmosphere.**

In this talk: cosmic rays colliding inelastically with a target, producing mesons that might decay into boosted dark matter particles. The source for the target can be the Interstellar Medium or the Atmosphere.

<table>
<thead>
<tr>
<th></th>
<th>Typical Density</th>
<th>Typical Length</th>
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<tbody>
<tr>
<td>ISM</td>
<td>$10^0$ cm$^{-3}$</td>
<td>$\mathcal{O}(10)$ kpc</td>
</tr>
<tr>
<td>Earth’s Atm</td>
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