Novel gamma-ray features from dark matter cascade processes involving scalar and fermions as intermediate states

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Based on works done in collaboration with:
A. Ibarra, M. Pato, E. Molinaro
1. Gamma rays from cascade processes
2. Models and physical realisations
3. Comparing with experimental data
4. Conclusions
Dark matter indirect detection

Gamma-rays from cascade processes
Direct Detection

DM + nucleus $\rightarrow$ DM + nucleus

Indirect Detection

DM + DM $\rightarrow$ $e^\pm, \gamma, p^\pm$

Collider Searches

p + p $\rightarrow$ DM + X
Direct Detection

DM + nucleus → DM + nucleus

Indirect Detection

DM + DM → e^±, γ, p^±

Collider Searches

p + p → DM + X
Spectral features
Spectral features

- Studying diffuse emission of multi-wavelength photons is plagued with uncertainties, mainly due to an unknown background
Spectral features

- Studying diffuse emission of multi-wavelength photons is plagued with uncertainties, mainly due to an unknown background.

- An observation in this channel would be subject to many tests before we claim a discovery.

\[ m_\chi = 150 \text{ GeV} \]
\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]
\[ \chi\chi \to b\bar{b} \]
Spectral features
• Instead of struggling with the background consider a case where the spectrum of DM origin differs from the power-law background
Spectral features

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\[ \Phi(E) \]

\[ E \]
• Instead of struggling with the background consider a case where the spectrum of DM origin differs from the power-law background
Indirect Detection with Gamma rays

Gamma-rays spectral features
Indirect Detection with Gamma rays

Gamma-rays spectral features

- Spectral features present a very clean way to pinpoint dark matter ➔ Smoking gun
Indirect Detection with Gamma rays

Gamma-rays spectral features

- Spectral features present a very clean way to pinpoint dark matter \(\rightarrow\) Smoking gun

1. Gamma-ray lines
Indirect Detection with Gamma rays

Gamma-rays spectral features

- Spectral features present a very clean way to pinpoint dark matter
  - Smoking gun

1. Gamma-rays from dark matter decay to electrons

\[
\chi_0 \rightarrow \tilde{e} \rightarrow e^- e^+ \rightarrow \gamma + \gamma
\]
Indirect Detection with Gamma rays

Gamma-rays spectral features

• Spectral features present a very clean way to pinpoint dark matter → Smoking gun
  1. Gamma-ray lines
  2. Internal Bremsstrahlung
Indirect Detection with Gamma rays

Gamma-ray spectral features

- Spectral features present a very clean way to pinpoint dark matter
  ➔ Smoking gun

1. Gamma-ray lines
2. Internal Bremsstrahlung

\[ \chi \to f \bar{f} \gamma \]
Indirect Detection with Gamma rays

Gamma-rays spectral features

• Spectral features present a very clean way to pinpoint dark matter \( \rightarrow \) Smoking gun

1. Gamma-ray lines

2. Internal Bremsstrahlung

3. Gamma-ray boxes and triangles
Indirect Detection with Gamma rays

Gamma-ray spectral features

• Spectral features present a very clean way to pinpoint dark matter

1. Gamma-ray lines

2. Internal Bremsstrahlung

3. Gamma-ray boxes and triangles
One-step cascades and “boxed” spectra

• Consider the process:

\[ \chi \chi \rightarrow \phi \phi \implies \phi \rightarrow \gamma X \]
One-step cascades and “boxed” spectra

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\[ \chi \chi \rightarrow \phi \phi \quad \Rightarrow \quad \phi \rightarrow \gamma X \]
One-step cascades and “boxed” spectra

- Consider the process:

\[ \chi \chi \rightarrow \phi \phi \quad \Longrightarrow \quad \phi \rightarrow \gamma X \]
One-step cascades and “boxed” spectra

• Consider the process:

\[ \chi \chi \rightarrow \phi \phi \quad \implies \quad \phi \rightarrow \gamma X \]

\[ \begin{aligned}
\chi & \\
\phi & \\
\chi & \\
\phi & \\
\end{aligned} \]

• Energy of the photons on the r.f. of \( \phi \)

\[ E_{\gamma}^{\text{RF}} = \frac{1}{2} \delta_{\phi X} m_\chi \quad \text{and} \quad \delta_{\phi X} = 1 - \frac{m_X^2}{m_\phi^2} \]
One-step cascades and “boxed” spectra

• Consider the process:

\[
\chi\chi \rightarrow \phi\phi \implies \phi \rightarrow \gamma X
\]

\[
E_{\gamma}^{\text{lab}} = \frac{1}{2} \delta_{\phi} X m_{\chi} (1 + \beta \cos \theta)
\]
One-step cascades and “boxed” spectra

• Consider the process:

\[ \chi\chi \rightarrow \phi\phi \implies \phi \rightarrow \gamma X \]

• In the lab frame:

\[ E_{\gamma}^{\text{lab}} = \frac{1}{2} \delta_X m_\chi (1 + \beta \cos \theta) \]
Scalars or fermions

• The intermediate be either a scalar or a fermion
Scalars or fermions

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Dirac Fermions

- Angular distribution of the radiated photons

\[ \frac{dN^{RF}}{d \cos \vartheta} = \frac{1}{2} (1 - \alpha \cos \vartheta) \]

- Decay modes: \( \psi \rightarrow \nu \gamma \)
Scalars or fermions

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**Dirac Fermions**

- Angular distribution of the radiated photons

\[
\frac{dN_{RF}}{d \cos \vartheta} = \frac{1}{2} (1 - \alpha \cos \vartheta)
\]

- Decay modes: \( \psi \rightarrow \nu \gamma \)

**Scalars and Majorana F.**

- Isotropic radiation of photons in the rest frame of the scalar

\( \alpha = 0 \)

- Decay modes: \( \phi \rightarrow \gamma \gamma \) or \( \phi \rightarrow \gamma Z \)
One-step cascades with scalars

• Consider the process:
One-step cascades with scalars

- Consider the process:

\[ \frac{dN}{dE} \]

\[ E_- \quad E_C \quad E_+ \quad E \]
One-step cascades with scalars

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\[
\frac{dN}{dE}
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\[E_-, \quad E_C, \quad E_+\]
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\[ E_+ \quad E_C \quad E_- \]

\[ E \]
One-step cascades with fermions

• Consider the process:
One-step cascades with fermions

- Consider the process:

\[
dN/dE \quad E_-, \quad E_C, \quad E_+ \quad E
\]
One-step cascades with fermions

- Consider the process:

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One-step cascades with fermions

• Consider the process:

\[ \frac{dN}{dE} \]

\[ E^- \quad E_C \quad E^+ \]

Graph showing the energy distribution with three points: \( E^- \), \( E_C \), and \( E^+ \).
One-step cascades with fermions

- Consider the process:

\[ \frac{dN}{dE} \]
One-step cascades with fermions

- Consider the process:

\[ \frac{dN}{dE} \]

\[ E_- \quad E_C \quad E_+ \]

Graph showing the energy distribution with different energy levels.
One-step cascades with fermions

- Consider the process:

\[ \frac{dN}{dE} \]

\[ E^{-} \quad E_{C} \quad E^{+} \]

\[
\begin{align*}
\frac{dN}{dE} & \\
E & \\
\end{align*}
\]
One-step cascades with fermions

- Consider the process:

\[ \frac{dN}{dE} \]

\[
\frac{dN_{RF}}{d \cos \vartheta} = \frac{1}{2} \left(1 - \alpha \cos \vartheta \right)
\]

\[ \alpha > 0 \]
One-step cascades with fermion

- Consider the process:

\[
\frac{dN^{RF}}{d \cos \vartheta} = \frac{1}{2} (1 - \alpha \cos \vartheta)
\]

\[\alpha < 0\]
Expected flux at earth:

\[ \phi_\gamma(E_\gamma) = \frac{d^4N_\gamma}{dE_\gamma dS d\Omega dt} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN_{\gamma}}{dE_\gamma} \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega J_{\text{ann}} \]

\[ \delta_{\chi \phi} = 1 - \frac{m_\phi^2}{m_\chi^2} \]

- narrow: \( \delta_{\chi \phi} = 0.002 \)
- intermediate: \( \delta_{\chi \phi} = 0.2 \)
- wide: \( \delta_{\chi \phi} = 0.99 \)
• Expected flux at earth:

\[
\phi_\gamma(E_\gamma) = \frac{d^4N_\gamma}{dE_\gamma dS d\Omega dt} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN_{\gamma}^{\text{res}}}{dE_\gamma} \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega J_{\text{ann}}
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\[\delta_{\chi\psi} = 1 - \frac{m_\psi^2}{m_\chi^2}\]

narrow  \[\delta_{\chi\psi} = 0.002\]

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• **Expected flux at earth:**

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\]

\[
\frac{dN^{RF}}{d \cos \vartheta} = \frac{1}{2} (1 - \alpha \cos \vartheta)
\]

**forward**

\( \alpha > 0 \)

**backward**

\( \alpha < 0 \)
Expected flux at earth:

\[ \phi_\gamma(E_\gamma) = \frac{d^4N_\gamma}{dE_\gamma dS d\Omega dt} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle dN^{\text{res}}_\gamma}{2m_\chi^2 dE_\gamma} \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega J_{\text{ann}} \]

\[ \delta_{\psi \nu} = 1 - \frac{m_\nu^2}{m_\psi^2} \]

- High energies: \( \delta_{\psi \nu} = 1 \)
- Low energies: \( \delta_{\psi \nu} = 0.25 \)
Models and physical realisations
What do we need?
What do we need?

- A stable—or long lived—dark matter particle
What do we need?

• A stable—or long lived—dark matter particle

• An intermediate state—fermion or scalar—which couples to DM
What do we need?

• A stable—or long lived—dark matter particle

• An intermediate state—fermion or scalar—which couples to DM

• A decay channel of the i.s. into photons (with sizeable BR)
Models for boxes

• Models involving the U(1) SSB and PQ mechanism
Models for boxes

- Models involving the U(1) SSB and PQ mechanism

1. A DM Dirac fermion $\chi$, a scalar $s$, and a pseudo scalar $a$

2. Different annihilation modes $\chi\chi \rightarrow as$, $\chi\chi \rightarrow aa$ and $\chi\chi \rightarrow ss$ depending on $\delta\chi a$

3. Branching ratio $a \rightarrow \gamma\gamma$ of 20-100% depending on the choice of the anomaly factors involved

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)
Models for boxes

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(Motivated by the galactic positron excess)

1. A TeV DM Dirac fermion $\chi$ with dominant annihilation mode $\chi\chi\rightarrow as$ (s-wave)

2. BR into photons of $\approx 10^{-3}$; simultaneously boost factor of $\approx 10^3$

3. Only wide boxes

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)

Y. Nomura, J. Thaler (arXiv:0810.5397)
Models for triangles

- If the intermediate states are Majorana, boxes are produced $\rightarrow$ intermediate states have to be Dirac

- Intermediate states are Dirac $\rightarrow$ U(1) charge, this means dm has also to be Dirac

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \partial_\mu S \partial^\mu S + i \overline{\chi} \partial \phi \chi + i \overline{\tilde{N}}_D \phi N_D - \frac{1}{2} \mu_S^2 S^2 - M_\chi \overline{\chi} \chi - M_N \overline{\tilde{N}}_D N_D$$

$$- (\lambda_\alpha \overline{L}_\alpha N_D H + f \overline{N}_D P_{L,R} \chi S + \text{h.c.}) - V(H, S),$$

Preliminary
Models for triangles

Ongoing work in collaboration with A. Ibarra, E. Molinaro, M. Pato.

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<table>
<thead>
<tr>
<th>Field</th>
<th>$L_\alpha$</th>
<th>$e_{R\alpha}$</th>
<th>$\bar{N}_D$</th>
<th>$\chi$</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U(1)_X$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>
Models for triangles

\[
\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \partial_\mu S \partial^\mu S + i \overline{\chi} \phi \chi + i \overline{N}_D \phi N_D - \frac{1}{2} \mu_S^2 S^2 - M_\chi \overline{\chi} \chi - M_N \overline{N}_D N_D
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\]
Models for triangles

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \partial_\mu S \partial^\mu S + i \bar{\chi} \phi \chi + i \bar{N}_D \phi N_D - \frac{1}{2} \mu_S^2 S^2 - M_X \bar{\chi} \chi - M_N \bar{N}_D N_D - (\lambda_{\alpha} \bar{L}_\alpha N_D H + \bar{N}_D P_{L,R} \chi S + \text{h.c.}) - V(H, S), \]

- If Yukawa was not chiral → equal amount of right and left handed sterile Neutrinos → boxes

- Asymmetric dark matter (ADM) and U(1) symmetry identified with lepton charge
Models for triangles

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\[ \chi \chi \rightarrow N_{D,R} N_{D,R} \rightarrow \gamma \gamma + \nu \nu \]
Models for triangles

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- If Yukawa was not chiral $\rightarrow$ equal amount of right and left handed sterile Neutrinos $\rightarrow$ boxes

- Asymmetric dark matter (ADM) and $U(1)$ symmetry identified with lepton charge

\[ \chi \chi \rightarrow N_{D,R} N_{D,R} \rightarrow \gamma \gamma + \nu \nu \]

- First clear indirect detection signal for ADM models
Comparing with experimental data
Upper limits on the cross section
Upper limits on the cross section

• We draw limits on the annihilation cross section for all the possible phenomenologies
Upper limits on the cross section

- We draw limits on the annihilation cross section for all the possible phenomenologies.
- We perform a sliding-window profile likelihood analysis all the sets of mock data.
Upper limits on the cross section

• We draw limits on the annihilation cross section for all the possible phenomenologies

• We perform a sliding-window profile likelihood analysis all the sets of mock data

• We use three different sets of data: H.E.S.S., Fermi and CTA (prospects)
Upper limits on the cross section

Using Fermi-LAT data from arXiv:1101.2610

- Varying the box/triangle width $\rightarrow \delta_{\chi\psi}$ or $\delta_{\chi\psi}$

$$\epsilon = 2 \quad \delta_{\psi\nu} = 1$$

![Graphs showing upper limits on the cross section for different masses and scales, labeled narrow, intermediate, and wide. Each graph shows the cross section in cm$^2$/s as a function of $m_x$ in GeV. The preliminary status is indicated.]
Upper limits on the cross section

Using Fermi-LAT data from arXiv:1101.2610

- Varying the centre of the triangle $\rightarrow \delta_{\psi \nu}$

$\epsilon = 2 \quad \delta_{\chi \psi} = 0.1$

![Graph showing cross section limits for high and low energies.](image)
Prospects on CTA


• 2\(\sigma\) upper limits and 5\(\sigma\) sensitivity to gamma-ray boxes for the upcoming CTA experiment

![Graphs showing 2\(\sigma\) upper limits and 5\(\sigma\) sensitivity for different mass regions (narrow, intermediate, wide).](image-url)
Prospects on CTA


\[ \langle \sigma v \rangle_0 (\text{cm}^3\text{s}^{-1}) \]

\[ m_\chi \text{ [TeV]} \]

- CTA $\epsilon_2$
- CTA $\epsilon_2$ (new performance)
- H.E.S.S. 2013
- Fermi-LAT 2013
Conclusions
Conclusions

• Spectral features in the gamma-ray sky would be an unequivocal signal of dark matter

→ If not observed it constrains strongly such scenarios

• Gamma-ray boxes are a third kind of spectral features that show naturally in some scenarios circumventing issues such as fine tuning

• There are feasible models that have such a behaviour and through this analysis we may set powerful limits on such scenarios

• Gamma-ray triangles are the only known DMID signal known for a ADM scenario
Thank you for your attention!!
Varying the window width $\epsilon$

$\delta \chi \phi (\delta \chi \phi) = 0.001 \quad \delta \psi \nu = 1$
Upper limits on the cross section

Using Fermi-LAT data from arXiv:1101.2610

- Varying the window width $\rightarrow \epsilon$

\[
\delta \chi \phi(\delta \chi \phi) = 0.001 \quad \delta \psi \nu = 1
\]
Performance of CTA
Prospects on CTA for boxes


• We deliver prospects on the upper limits and sensitivity for the forthcoming CTA experiment

• Using information delivered by the CTA consortium we simulate 300 sets of mock data using a well motivated background:
  • Protons
  • gamma rays
  • gc point source
  • electrons/positrons

Prospects on CTA

Prospects on CTA


- We perform a sliding-window profile likelihood analysis all the sets of mock data
Prospects on CTA


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Concrete model A

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)
Concrete model A
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Setup:

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- Dirac dark matter $\chi$ and a complex scalar $S$
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![Diagram](image)

- Narrow box $\text{BR} < 0.1$
- $\sim 0.9$
Concrete model A

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)

- Dirac dark matter $\chi$ and a complex scalar $S$
- PQ mechanism $\rightarrow$ scalar $s$ and pseudoscalar $a$

Wide box $\sim 0.5$

$\sim 0.25$

$\sim 0.5$

$\sim 0.25$
Concrete model B

Y. Nomura, J. Thaler (arXiv:0810.5397)
Concrete model B

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(Motivated by the galactic positron excess)

Setup:
Concrete model B

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Setup:

1. A TeV DM Dirac fermion $\chi$ with dominant annihilation mode $\chi\chi \to as$ (s-wave)
Concrete model B

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2. BR into photons of $\sim 10^{-3}$
Concrete model B

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Setup:

1. A TeV DM Dirac fermion $\chi$ with dominant annihilation mode $\chi\chi \rightarrow as$ (s-wave)

2. BR into photons of $\sim 10^{-3}$

3. The scalar $s$ is responsible for a boost factor of $\sim 10^3$
Concrete model B

Y. Nomura, J. Thaler (arXiv:0810.5397)

- Such a theory arises naturally where $m_\chi$ is generated by the SSB of a global $U(1)_X$ symmetry ($X \rightarrow PQ$) $a$ is the axion-like particle related to this symmetry

- Physical parameters:

  \[ m_\chi = 1 \text{ TeV} \]
  \[ 360 \text{ MeV} \lesssim m_a \lesssim 800 \text{ MeV} \]
Concrete model B

Y. Nomura, J. Thaler (arXiv:0810.5397)

• Such a theory arises naturally where $m_\chi$ is generated by the SSB of a global $U(1)_X$ symmetry ($X \rightarrow PQ$) $\alpha$ is the axion-like particle related to this symmetry.

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\[ 360 \text{ MeV} \lesssim m_\alpha \lesssim 800 \text{ MeV} \]

Wide box
Models A and B

A:

\[ \langle \sigma v \rangle_{0}^{4\gamma} = \langle \sigma v \rangle_{0} \left( \text{BR}(\chi \bar{\chi} \to aa) + \frac{\text{BR}(\chi \bar{\chi} \to as)}{2} \right) \text{BR}(a \to \gamma \gamma), \]

B:

\[ \langle \sigma v \rangle_{0}^{4\gamma} = B_{S} \langle \sigma v \rangle_{0} \frac{\text{BR}(\chi \bar{\chi} \to as)}{2} \text{BR}(a \to \gamma \gamma). \]

<table>
<thead>
<tr>
<th></th>
<th>( m_{a}/m_{\chi} )</th>
<th>\text{BR}(\chi \bar{\chi} \to as)</th>
<th>\text{BR}(\chi \bar{\chi} \to aa)</th>
<th>\text{BR}(\chi \bar{\chi} \to ss)</th>
<th>\langle \sigma v \rangle_{0}/\langle \sigma v \rangle_{\text{th}}</th>
<th>\text{References}</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (narrow)</td>
<td>0.999</td>
<td>0.99</td>
<td>( 2 \times 10^{-3} )</td>
<td>( 4 \times 10^{-3} )</td>
<td>0.13</td>
<td>[39, 56, 57]</td>
</tr>
<tr>
<td>A2 (intermediate)</td>
<td>0.9</td>
<td>0.64</td>
<td>0.12</td>
<td>0.24</td>
<td>0.76</td>
<td>[39, 56, 57]</td>
</tr>
<tr>
<td>A3 (wide)</td>
<td>0.1</td>
<td>0.25</td>
<td>0.25</td>
<td>0.50</td>
<td>0.96</td>
<td>[39, 56, 57]</td>
</tr>
<tr>
<td>B (wide)</td>
<td>0.1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>[58–60]</td>
</tr>
</tbody>
</table>
Limits on the models


• Comparing with our previous prospects on CTA
Concrete model

Ibarra, Lee, SLG, Park, Pato (arXiv:0810.5397)

- Branching ratio of $a$ into two photons
Limits on the models

Limits on the models


• Comparing with our previous prospects on CTA