Indirect searches of dark matter via polynomial spectral features

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Outline

● Part I: Motivation
  Box-shaped gamma-ray spectra

● Part II: Another example
  Neutrino features from DM annihilating into SM gauge bosons

● Part III: General case
  Polynomial spectral features

● Conclusions
Gamma-ray spectral features

Smoking gun signature for dark matter: no astrophysical process is known to produce a sharp feature in the gamma-ray spectrum

Annihilation into Photons

Virtual Internal Bremsstrahlung (VIB)

Box-shaped spectra

![Graph showing gamma-ray spectra features](image-url)
**Gamma-ray spectral features**

**Smoking gun signature for dark matter**: no astrophysical process is known to produce a sharp feature in the gamma-ray spectrum.

- **Annihilation into Photons**
- **Virtual Internal Bremsstrahlung (VIB)**
- **Box-shaped spectra**

![Graph showing gamma-ray spectral features](image)

- Originally studied for scalar mediators

**Graph Details**

- $\Delta E/E = 0.15$
- $\Delta E/E = 0.02$

**Axes**

- $x = E / m_X$
- $x^2 dN/dx$

**Legend**

- $q \bar{q}$, $ZZ$, $WW$
- VIB
- Box
- $\gamma \gamma$
Gamma-ray spectral features
Smoking gun signature for dark matter: no astrophysical process is known to produce a sharp feature in the gamma-ray spectrum.

Annihilation into Photons
Virtual Internal Bremsstrahlung (VIB)
Box-shaped spectra

Originally studied for scalar mediators
This talk: Generalize this to an arbitrary intermediate state
Box-shaped spectra from intermediary scalars

\[ m_{\text{DM}} = 100 \text{ GeV} \]
\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \]

Ibarra et. al 2012
The same applies to neutrinos
The same applies to neutrinos
The same applies to neutrinos.
The case of gauge bosons
The case of gauge bosons
The case of gauge bosons

\[
\frac{d\Phi_\nu}{dE_\nu} = \Phi_\nu \sum_m Br_m \frac{dN_{\nu,m}}{dE_\nu}, \quad \Phi_\nu = \frac{(\sigma v)}{8\pi M_{DM}^2} \bar{J}_{\text{ann}}
\]
The case of gauge bosons

\[
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\]
The case of gauge bosons
The case of gauge bosons

Gauge bosons produced in DM annihilations are typically polarized

Above the electroweak scale, Majorana DM with $SU(2)_L$ quantum numbers produce gauge bosons that are mostly transverse.

Scalar DM, also singlet under $SU(2)_L$, produces gauge bosons that are mostly longitudinally polarized.
General case
General case
General case

\[ \theta_0 \langle m', S|m, S \rangle = \langle m', S|R(\theta_0)|m, S \rangle \equiv d^S_{m', m}(\theta_0) \]
General case

\[ \theta_0 \langle m', S|m, S \rangle = \langle m', S|R(\theta_0)|m, S \rangle \equiv d_{m', m}^S(\theta_0) \]

\[ (\Phi_A)^{-1} \frac{d\Phi_A}{dE_A} = \frac{1}{n} \sum_m Br_m \frac{dN_{A,m}}{dE_A} \]

\[ = \frac{1}{M_{DM}} \sum_m Br_m f_m^S \left( \frac{E_A}{M_{DM}}, \frac{E_X}{M_{DM}} \right) \]
General case

\[ \theta_0 \langle m', S|m, S \rangle = \langle m', S|R(\theta_0)|m, S \rangle \equiv d_{m,m}^S(\theta_0) \]

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= \frac{1}{M_{DM}} \sum_m Br_m f_m(S) \left( \frac{E_A}{M_{DM}}, \frac{E_X}{M_{DM}} \right)
\]

\[
f_m^S(x, y) = \frac{(2S + 1)}{\sqrt{y^2 - r_X^2}} \Theta(x - x^{-}(y)) \Theta(x^{+}(y) - x) \\
\times \sum_{m'} C_{m'} \left| d_{m'm}^S \left( \arccos \left( \frac{2x - y}{\sqrt{y^2 - r_X^2}} \right) \right) \right|^2
\]
Almost everything fixed by angular momentum.

The dependence on the DM Model is encoded in two quantities:

\[
\theta_0 \langle m', S | m, S \rangle = \langle m', S | R(\theta_0) | m, S \rangle \equiv d_{m', m}^S(\theta_0)
\]

\[
(\Phi_A)^{-1} \frac{d\Phi_A}{dE_A} = \frac{1}{n} \sum_m B_{m} \frac{dN_{A,m}}{dE_A}
= \frac{1}{M_{\text{DM}}} \sum_m B_{m} \rho_S \left( \frac{E_A}{M_{\text{DM}}} \right) \left( \frac{E_X}{M_{\text{DM}}} \right)
\]

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\[
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Fixed by the DM model.
It determines the degree of polarization.
General case

Almost everything fixed by angular momentum.

The dependence on the DM Model is encoded in two quantities

\[ f_m(x, y) = \frac{(2S + 1)}{\sqrt{y^2 - r_X^2}} \Theta (x - x^-(y)) \Theta (x^+(y) - x) \]
\[ \times \sum_{m'} |C_{m'}|^2 d_{m'm}^S \left( \arccos \left( \frac{2x - y}{\sqrt{y^2 - r_X^2}} \right) \right)^2 \]

\[ \theta_0 \langle m', S|m, S \rangle = \langle m', S|R(\theta_0)|m, S \rangle \equiv d_{m'm}^S(\theta_0) \]

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Fixed by the DM model.
It determines the degree of polarization
Example with particles of Spin-2

For spin-2 particles coupled to the energy-momentum tensor

<table>
<thead>
<tr>
<th>final state $AB$</th>
<th>$C_{-2}$</th>
<th>$C_{-1}$</th>
<th>$C_0$</th>
<th>$C_1$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$\frac{6}{13}$</td>
<td>0</td>
<td>$\frac{1}{13}$</td>
<td>0</td>
<td>$\frac{6}{13}$</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>$\frac{6}{13}$</td>
<td>0</td>
<td>$\frac{1}{13}$</td>
<td>0</td>
<td>$\frac{6}{13}$</td>
</tr>
<tr>
<td>$hh$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_L\bar{\nu}_L$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_R\bar{\nu}_R$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\nu\bar{\nu}$ (Dirac or Majorana)</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
</tr>
</tbody>
</table>

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Fixed by the properties of the particle X and the final state
Are spin-2 particles arising in DM annihilations polarized?

Are they coupled to the energy-momentum tensor?
Are spin-2 particles arising in DM annihilations polarized?

**Boosted regime**  \( M_T^2 \ll p^2 \)

\[
\begin{align*}
\varepsilon^{\mu\nu}(\pm 2) &= \varepsilon^\mu(\pm)\varepsilon^\nu(\pm), \\
\varepsilon^{\mu\nu}(\pm 1) &\approx \frac{1}{\sqrt{2}M_T} [p^\nu\varepsilon^\mu(\pm) + p^\mu\varepsilon^\nu(\pm)] \\
\varepsilon^{\mu\nu}(0) &\approx \frac{\eta^{\mu\nu}}{\sqrt{6}} + \sqrt{\frac{2}{3}} \frac{p^\mu p^\nu}{M_T^2}.
\end{align*}
\]

Are they coupled to the energy-momentum tensor?

No

The spin-2 particles are mostly polarized with  \( m = 0 \)

\( \text{Br}_{0,0} = 1 \)
Are spin-2 particles arising in DM annihilations polarized?

Are they coupled to the energy-momentum tensor?

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States with $m = \pm 1$

naturally decouple. Is there a selection rule forbidding $m = 0$?

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Are they coupled to the energy-momentum tensor?

- Yes
- No

States with \( m = \pm 1 \) naturally decouple. Is there a selection rule forbidding \( m = 0 \)?

- No
- Yes

The spin-2 particles are mostly polarized with \( m = 0 \)

- \( \text{Br}_{0,0} = 1 \)

The spin-2 particles are mostly polarized with \( m = \pm 2 \)

- \( \text{Br}_{2,2} = \text{Br}_{-2,-2} = 1/2 \)
DM DM → TT, $T \rightarrow \gamma\gamma$ with $M_T/M_{DM} = 0.01$

$\gamma^{-1}d\gamma^{-1}/dx$

$Br_{0,0} = 1$

$Br_{2,2} = Br_{-2,-2} = 1/2$

unpolarized

$x = E_\gamma/M_{DM}$

DM DM → TT, $T \rightarrow \gamma\gamma$ with $M_T/M_{DM} = 0.75$

$Br_{0,0} = 1$

unpolarized

$Br_{2,2} = Br_{-2,-2} = 1/2$

$x = E_\gamma/M_{DM}$
Example with a hypothetical diphoton resonance

\[ M_{DM} = 5 \text{ TeV}, \quad M_T = 0.75 \text{ TeV} \]

\[ \Delta E/E = 15\% \]

\[ Br_0 = 1, \quad Br_\pm = 1/2 \]
Example with a hypothetical diphoton resonance

$M_{DM} = 5 \text{ TeV}, M_T = 0.75 \text{ TeV}$

$\Delta E/E = 15\%$

$\text{Br}_{\phi,0} = 1$

$\text{Br}_{\phi,2} = Br_{\phi, -2} = 1/2$

$\Delta E/E = 5\%$

$\text{Br}_{\phi,0} = 1$

$\text{Br}_{\phi,2} = Br_{\phi, -2} = 1/2$
Example with a hypothetical diphoton resonance

H.E.S.S. Limits on spectral features

\[ M_T = 0.75 \text{ TeV} \]

\[ \sigma V(\text{DM DM} \rightarrow \text{TT}) \Br(\text{T} \rightarrow \gamma \gamma) \text{ (cm}^3 \text{/s)} \]

- \( \Br_{2,2} = \Br_{-2,-2} = 1/2 \)
- \( \Br_{0,0} = 1 \)
- unpolarized
- \( 2\sigma V(\text{DM DM} \rightarrow \gamma \gamma) \)
Example with a hypothetical diphoton resonance

H.E.S.S. Limits on spectral features

\[ M_T = 2 \text{ TeV} \]

\[ \sigma_v(\text{DM DM} \rightarrow \gamma\gamma) \text{ (cm}^3\text{/s)} \]

- unpolarized
- \( Br_{0,0} = 1 \)
- \( Br_{2,2} = Br_{-2,-2} = 1/2 \)

\[ 2\sigma_v(\text{DM DM} \rightarrow \gamma\gamma) \]
Conclusions

- DM annihilations into arbitrary particles that subsequently decay into photons or neutrinos lead to polynomial spectral features.

- Such features are generic and can be studied using a model-independent approach.

- Using this, high resolution of gamma-ray or neutrinos telescopes could tell the spin of the decaying particle.

- We calculate the annihilation spectrum that the associated to a diphoton resonance if DM annihilates or decays into it.