Introduction

Dark Matter Evidence

The Coma Cluster

Galactic rotation curves

The CMB spectrum

The Bullet cluster
Introduction

Dark Matter

What we know so far:

It is essential for galaxy formation

Its approximate abundance.
Introduction

Dark Matter

What we know so far:

- It is essential for galaxy formation
- Its approximate abundance.

What we don't know:

- What it actually is!
Introduction

Methods of Detection

Direct Detection

Scattering
Introduction
Methods of Detection

- Indirect Detection
- Annihilation
Introduction

Methods of Detection

Colliders

Production
Introduction
Theoretical Approaches

Effective Field Theories  Simplified Models  UV Complete Models
Introduction

Simplified Models

Dark Sector

Visible Sector

Portal

New Gauge Symmetries

SU(3)_c × SU(2)_L × U(1)_Y
1st Case of Study

The Dark Sequential Z' Portal

Dark Sector

Visible Sector

Portal

$\chi$

$U(1)'$

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$Z'$
1st Case of Study

The Dark Sequential Z' Portal

Majorana fermion

U(1)'

SU(3)_c \times SU(2)_L \times U(1)_Y

Portal

Visible Sector

Dark Sector

If the SM Higgs is not charged under U(1)', there is no mass mixing and Z' is the only portal. Here, Z' couples to the SM exactly as Z does, hence Sequential.
The Dark Sequential Z' Portal

Majorana fermion

Natural consequence of a symmetry breaking chain in GUTs and other extended groups.

If the SM Higgs is not charged under $U(1)'$, there is no mass mixing and $Z'$ is the only portal. Here, $Z'$ couples to the SM exactly as $Z$ does, hence Sequential.

$$\mathcal{L} \supset g_\chi \chi \gamma^\mu \gamma^5 \chi + \sum_{f \in SM} \bar{f} \gamma^\mu (g_{fv} + g_{fa} \gamma^5) f \right] Z'_\mu$$
1st Case of Study

The Dark Sequential $Z'$ Portal

Majorana fermion

Natural consequence of a symmetry breaking chain in GUTs and other extended groups.

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\[ \mathcal{L} \supset \left[ g_\chi \chi \gamma^\mu \gamma^5 \chi + \sum_{f \in \text{SM}} \bar{f} \gamma^\mu (g_{fv} + g_{fa} \gamma^5) f \right] Z'_\mu \]

- SI: velocity suppressed
- SD: 
  - $\bar{f} \gamma^\mu f \chi \gamma_\mu \gamma^5 \chi$: ✓
  - $\bar{f} \gamma^\mu \gamma_5 f \chi \gamma_\mu \gamma^5 \chi$: ✗
Constraints

Relic Density

\[ \Omega h^2 = 0.1199 \pm 0.012 \]

(through thermal production)

Calculated using **MicrOmegas 4.3.2.**
Constraints

Direct Detection

\[
\sigma_{\chi N}^{SD} = \frac{12\mu_{\chi N}^2}{\pi} \frac{g_x^2}{M_{Z'}^4} \left[ g_{ua} \Delta_u^N + g_{da} (\Delta_d^N + \Delta_s^N) \right]^2, \ N = p, n
\]
Constraints

Direct Detection

\[ \sigma_{\chi N}^{SD} = \frac{12 \mu_{XN}^2}{\pi} \frac{g_X^2}{M_{Z'}^4} \left[ g_{ua} \Delta_u^N + g_{da} \left( \Delta_d^N + \Delta_s^N \right) \right]^2, \quad N = p, n \]

(One unpaired proton in C₃F₈)

[\text{SD}_p]

(One unpaired neutron in Xe)

[\text{SD}_n]

\[ \chi \quad \chi \]

\[ Z' \]

\[ q \quad q \]


[XENON Collaboration, arXiv:1705.06655]

[XENON Collaboration, JCAP 1604 (2016) no.04, 027]

Constraints

Direct Detection 2

- Neutrino flux is connected to DM capture and annihilation.
- Once the equilibrium is reached the annihilation can be removed and limits can be imposed on the capture rate.
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\[ C_{\text{DM}} = 10^{20} \, s^{-1} \left( \frac{1 \text{ TeV}}{m_\chi} \right)^2 \frac{2.77 \, \sigma_{SD p} + 4270 \, \sigma_{SI p}}{10^{-40} \text{ cm}^{-2}} \]
Neutrino flux is connected to DM capture and annihilation.

Once the equilibrium is reached the annihilation can be removed and limits can be imposed on the capture rate.

\[ C_{\text{DM}} = 10^{20} \, \text{s}^{-1} \left( \frac{1 \, \text{TeV}}{m_\chi} \right)^2 \cdot \frac{2.77 \, \sigma_{SD}}{10^{-40} \, \text{cm}^{-2}} + 4270 \, \sigma_{SI} \]

Subdominant, but limits closer to those of DD Experiments (PICO-60).

Dominant, but limits coming from DD Experiments (XENON1T, LUX) are several orders of magnitude stronger.
Constraints

Colliders

Dileptons

Monojet

$q \rightarrow \ell \rightarrow Z'\ell$

$q \rightarrow g \rightarrow \chi Z'$
Monojet searches are based on events with missing energy peaking at DM pairs, hence the limits are for $M_\chi < M_{Z'}/2$

For 13 TeV and 36.1 fb$^{-1}$, it roughly excludes $M_{Z'} \approx 4$ TeV.

The limit weakens for $M_\chi < M_{Z'}$

$$\frac{\Gamma(Z' \rightarrow \ell\ell)}{\Gamma(Z' \rightarrow ff)} \Rightarrow \text{Br}(Z'_{SSM} \rightarrow \ell\ell)[1 - \text{Br}(Z' \rightarrow \chi\chi)]$$
As this is *not* a UV complete theory, the model exhibits an odd behavior in the process $\chi \chi \rightarrow Z' Z'$.

$$\sigma(\chi \chi \rightarrow Z' Z') \propto \frac{\sqrt{s} M_\chi}{M_{Z'}}$$

This is due to the contribution from $Z'_L$ to the diagram. Unitarity can be restored once the scalar that breaks $U(1)'$ is introduced.
As this is not a UV complete theory, the model exhibits an odd behavior in the process \( \chi\chi \rightarrow Z'Z' \)

\[
\sigma(\chi\chi \rightarrow Z'Z') \propto \frac{\sqrt{s} M_\chi}{M_{Z'}}
\]

This is due to the contribution from \( Z'_L \) to the diagram. Unitarity can be restored once the scalar that breaks \( U(1)' \) is introduced.

Hence, a limit on the validity of our results can be translated as

\[
M_\chi > \sqrt{\frac{\pi M_{Z'}}{2 g^2_\chi}}
\]

Results
Results
Results
2nd Case of Study

The Neutrino Portal

Dark Sector

Portal

Visible Sector

SU(3)c×SU(2)L×U(1)Y

φ

?
2nd Case of Study

The Neutrino Portal

For example $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ with 3 right handed neutrinos to avoid anomalies.
2nd Case of Study

The Neutrino Portal

Dark Sector

Portal

Visible Sector

Assumption: Dark matter interacts only with sterile neutrinos, that have seesaw I interactions.

For example $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ with 3 right handed neutrinos to avoid anomalies.
Fermi-LAT: Pair-conversion telescope.

Characteristics:
- Energy range: 20 MeV - 300 GeV
- Effective area: ~ 1 m²
- Field of view: 2.4 sr
- Background: Terrestrial gamma rays, GRBs and solar flares.
Constraints

Indirect Detection

H.E.S.S: Imaging Air Cherenkov Telescope.

Characteristics:
- Energy range: 200 GeV - 10 TeV
- Effective area: $\sim 10^5$ m²
- Field of view: 5 deg
- Background: Cosmic rays, events from the inner band of the GC.
Method

The differential flix (the astro-particle connection)

\[ \frac{d\Phi_\gamma (\Delta \Omega)}{dE} (E_\gamma) = \frac{1}{4\pi} \frac{\sigma v}{2M_{DM}^2} \frac{dN_\gamma}{dE_\gamma} \cdot J_{\text{ann}} \]
Method

The differential flux (the astro-particle connection)

\[
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Method

The differential flux (the astro-particle connection)

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Particle physics

Astrophysics

PYTHIA 8.219

[Cirelli, Marco, arXiv:1511.02031v3]
Results

Table:

- \( \langle \sigma v \rangle \) [cm\(^3\)/s] for different masses:
  - \( M_N = 10 \) GeV
  - \( M_N = 100 \) GeV
  - \( M_N = 1 \) TeV

Graph:

- \( \ell = e \)
- 95% C.L.
- Fermi-LAT
- Thermal production

Legend:

- \( \langle \sigma v \rangle \) in GeV
- \( M_{DM} \) in GeV
Results

\[ \langle \sigma v \rangle \, [\text{cm}^3/\text{s}] \]

\begin{align*}
10^{-27} & \quad 10^{-26} & \quad 10^{-25} & \quad 10^{-24} & \quad 10^{-23} & \quad 10^{-22} \\
10^5 & \quad 10^6 & \quad 10^7 & \quad 10^8 & \quad 10^9 & \quad 10^{10} \\
95\% \text{ C. L.} & & & & & \\
\end{align*}

- \[ M_N = 10 \text{ GeV} \]
- \[ M_N = 100 \text{ GeV} \]
- \[ M_N = 1 \text{ TeV} \]

\[ \ell = \tau \]

Fermi-LAT

HESS
Conclusions

We have investigated two different simplified models of dark matter and their phenomenological implications.

The complementarity among the different probes has been assessed, noticing that depending on the characteristics of the model, not all dark matter experiments have the same impact.

In the Dark Sequential Z' Portal model we revisited the status of a Majorana fermion as a dark matter particle, and by doing a full experimental scan we outlined the parameter space where this is a successful candidate.

In the Neutrino Portal model we concluded that, despite experimentally challenging small mixing angles of the heavy neutrinos, interesting limits can be imposed using indirect detection, ruling out masses up to ~200 GeV for thermally produced dark matter.
Thank you!
\begin{equation}
\langle \sigma v \rangle_{Z',Z'} = \frac{g_{\chi}^4}{\pi m_\chi^2} \left(1 - \frac{M_{Z',Z'}^2}{m_\chi^2} \right)^{\frac{3}{2}} \left(1 - \frac{M_{Z',Z'}^2}{2m_\chi^2} \right)^{-2} \\
+ \frac{g_{\chi}^4 v^2}{3\pi m_\chi^2} \sqrt{1 - \frac{M_{Z',Z'}^2}{m_\chi^2}} \left(1 - \frac{M_{Z',Z'}^2}{2m_\chi^2} \right)^{-4} \left( \frac{23 M_{Z',Z'}^6}{16 m_\chi^6} - \frac{59 M_{Z',Z'}^4}{8 m_\chi^4} + \frac{43 M_{Z',Z'}^2}{4 m_\chi^2} + 2 - 12 \frac{m_\chi^2}{M_{Z',Z'}^2} + 8 \frac{m_\chi^4}{M_{Z',Z'}^4} \right). 
\end{equation}

\[ \chi \quad \text{---} \quad Z' \]

\[ \chi \quad \text{---} \quad Z' \]
Energy spectrum for different final state leptons

- $M_{DM} = 1$ TeV
- $M_N = 500$ GeV

- $\ell = e$
- $\ell = \mu$
- $\ell = \tau$
Backup Slides

Reproducing previous results

Fermi-LAT

H.E.S.S.

WW final state

$\sigma_v \, [\text{cm}^3/\text{s}]$

$qq$ final state

$\sigma_v \, [\text{cm}^3/\text{s}]$
Backup Slides
Comparison with previous results

Fermi-LAT

H.E.S.S.

\( \langle \sigma v \rangle \) (cm\(^3\)s\(^{-1}\))

\( m_{\text{DM}} \) (GeV/c\(^2\))

254h, DM DM → WW

Einasto profile

Thermal relic density

Thermal relic cross section

(Stodgier et al. 2012)
Comparison between sources

**dSphs**

- **Characteristics:**
  - J-factors $\sim 10^{19} \text{ GeV}^2 \text{ cm}^{-5}$
  - Lack of non-thermal astrophysical processes.
  - Probe the low-$M_{\text{DM}}$ parameter space.

**GC**

- **Characteristics:**
  - J-factors $\sim 10^{21} \text{ GeV}^2 \text{ cm}^{-5}$
  - Gamma-ray emission from non-thermal processes makes a bright background.
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- J-factors \( \sim 10^{19} \text{ GeV}^2 \text{ cm}^{-5} \)
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Characteristics:
- J-factors \( \sim 10^{21} \text{ GeV}^2 \text{ cm}^{-5} \)
- Gamma-ray emission from non-thermal processes makes a bright background.
Small Digression

Why not Indirect Detection?

\[
\langle \sigma v \rangle_{ff} = \sum_f n_c^f \frac{2 \sqrt{m^2_\chi - m^2_f}}{\pi m_\chi M^4_{Z'}} \left( M^2_{Z'} - 4m^2_\chi \right)^2 \left[ (g_{fa})^2 g^2_\chi m^2_f (M^2_{Z'} - 4m^2_\chi)^2 \right] \\
- \frac{v^2}{6\pi m_\chi M^4_{Z'} \sqrt{m^2_\chi - m^2_f (M^2_{Z'} - 4m^2_\chi)^3}} \left[ (g_{fa})^2 \left\{ -g^2_\chi (M^2_{Z'} - 4m^2_\chi) \right\} \right] \\
\times \left( 23m^4_f M^4_{Z'} - 192m^2_f m^6_\chi - 4m^2_f m^2_\chi M^2_{Z'} \left( 30m^2_f + 7M^2_{Z'} \right) \\
+ 8m^4_\chi \left( 30m^4_f + 12m^2_f M^2_{Z'} + M^4_{Z'} \right) \right) \\
+ M^4_{Z'} (g_{fv})^2 \left\{ 4g^2_\chi \left( m^4_f + m^2_f m^2_\chi - 2m^4_\chi \right) (M^2_{Z'} - 4m^2_\chi) \right\} 
\]
Small Digression

Why not Indirect Detection?

\[
\langle \sigma v \rangle_{ff} = \sum_f n_c^f \frac{2 \sqrt{m_\chi^2 - m_f^2}}{\pi m_\chi M_{Z'}^4 (M_{Z'}^2 - 4m_\chi^2)^2} \left[ (g_{fa})^2 g_\chi^2 m_f^2 (M_{Z'}^2 - 4m_\chi^2)^2 \right] \\

- \frac{v^2}{6\pi m_\chi M_{Z'}^4 \sqrt{m_\chi^2 - m_f^2 (M_{Z'}^2 - 4m_\chi^2)^3}} \left[ (g_{fa})^2 \left\{ -g_\chi^2 (M_{Z'}^2 - 4m_\chi^2) \right\} \\
\times \left( 23m_f^4 M_{Z'}^4 - 192m_f^2 m_\chi^6 - 4m_f^2 m_\chi^2 M_{Z'}^2 \left( 30m_f^2 + 7M_{Z'}^2 \right) \right) \right] \\
+ M_{Z'}^4 (g_{fv})^2 \left\{ 4g_\chi^2 (m_f^4 + m_f^2 m_\chi^2 - 2m_\chi^4) (M_{Z'}^2 - 4m_\chi^2) \right\} \right] \\

velocity suppressed \propto v^2
\]