Inelastic Dark Matter and a Dark Higgs

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New trends in dark matter

ICTP SAIFR Brazil

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Thermal dark matter is a well-motivated and predictive scenario which can be probed with direct and indirect searches as well as with collider experiments.
Thermal Dark Matter Paradigm

Inelastic DM and a Dark Higgs

Zeldovich (1966)
Lee Weinberg (1977)
Dicus, Kolb, Teplitz (1977)

$\sigma v \sim 10^{-26} \text{cm}^3/s$
$\sigma \sim 1 \text{pb}$
m from subGeV to 100 TeV

$M = 100 \text{ GeV}$

Feng et al. (2010)

Thermal dark matter is a well motivated and predictive scenario which can be probed with direct and indirect searches as well as with collider experiments.

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Thermal Dark Matter Paradigm

Direct searches

Light dark matter does not have enough momentum to kick heavy nuclei

Loss of sensitivity mass for SubGeV masses.

Indirect searches

S-wave thermal cross sections are excluded by CMB observations
Inelastic Dark Matter

A simple scenario for light thermal dark matter which evades the strong CMB bounds is the case where DM couples inelastically to Standard Model.

Here a sufficiently large mass splitting between the DM particle $\chi_1$ and its heavier twin $\chi_2$ ensures that:

(i) direct detection limits are basically absent

(ii) residual DM annihilations are no longer efficient during the time of the CMB.

Smith, Weiner (2001)
A simple scenario for light thermal dark matter which evades the strong CMB bounds is the case where DM couples inelastically to Standard Model.

Here a sufficiently large mass splitting between the DM particle $\chi_1$ and its heavier twin $\chi_2$ ensures that:

(i) direct detection limits are basically absent
(ii) residual DM annihilations are no longer efficient during the time of the CMB.

Smith, Weiner (2001) start with $\psi$ a Dirac fermion charged under a $U(1)$ symmetry.

After $U(1)$ symmetry breaking

$$\chi_1 = \frac{\psi - \psi^c}{\sqrt{2}},$$

and

$$\chi_2 = \frac{\psi + \psi^c}{\sqrt{2}}.$$
\( B_{\mu\nu} V_{\mu\nu} \)  
“Kinetic mixing” with additional U(1)’ group

\( H^+ H (\lambda S^2 + A S) \)  
Higgs-singlet scalar interactions (scalar portal)

\( LH N \)  
neutrino Yukawa coupling, \( N \) – RH neutrino
$B_{\mu\nu} V_{\mu\nu}$

“Kinetic mixing” with additional U(1)' group

$H^+ H (\lambda S^2 + A S)$

Higgs-singlet scalar interactions (scalar portal)

$LH N$

neutrino Yukawa coupling, $N$ – RH neutrino
\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} \hat{X}_{\mu\nu} \hat{X}^{\mu\nu} - \frac{\epsilon}{2c_W} \hat{X}_{\mu\nu} \hat{B}^{\mu\nu} \]

Inelastic DM and a Dark Higgs

\( B_{\mu\nu} V_{\mu\nu} \)  
“Kinetic mixing” with additional U(1)’ group

\( H^+ H (\lambda S^2 + A S) \)  
Higgs-singlet scalar interactions (scalar portal)

\( \Lambda H N \)  
neutrino Yukawa coupling, \( N - \text{RH neutrino} \)

\( \chi_1, \chi_2 \)  
Dark Photon \( A' \)

\( A' \) inherits the coupling structure of the photon to the SM fermions where the electric charge is multiplied by a common factor \( \epsilon \).
Inelastic DM and a Dark Higgs

**Inelastic Dark Matter**

\[ \chi_1 \xrightarrow{A'} \text{fsm} \]

\[ \chi_2 \xrightarrow{A'} \text{fsm} \]

**Thermal Process**

\[ e^+ + e^- \rightarrow \gamma + \chi_1 \]

\[ \gamma \rightarrow \chi_1 + A' \]

\[ \chi_1 \rightarrow \mu^+ + \mu^- + h^+ + h^- \]

\[ \text{Take } m_{A'} > m_{\chi_1} \]

\[ \text{to avoid CMB constraints} \]

**Collider signatures**

**displaced vertices**

Izaguirre, Krnjaic, Shuve (2016)

Izaguirre, Kahn, Krnjaic, Moschella (2017)

Izaguirre, Kahn, Krnjaic, Moschella (2017)

Duerr, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg (2019)

**Vertex detector**

**Drift chamber**

**Calorimeter**

**Muon system**

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Open questions

What process generates the dark photon mass?

What induces the mass splitting \( \Delta = m_{\chi_2} - m_{\chi_1} \)?

Does it affect the phenomenology?

Invoke the dark Higgs mechanism:

\[
V(\phi, H) = \lambda_H \left( H^\dagger H - \frac{v_H^2}{2} \right)^2 + \lambda_\phi \left( \phi^* \phi - \frac{v_\phi^2}{2} \right)^2 + \lambda_{\phi H} \left( H^\dagger H - \frac{v_H^2}{2} \right) \left( \phi^* \phi - \frac{v_\phi^2}{2} \right)
\]

\[
\phi = \frac{v_\phi + \hat{\phi}^\prime}{\sqrt{2}}, \quad H = \begin{pmatrix} 0 & (v_H + \hat{h})/\sqrt{2} \end{pmatrix}^T
\]

\( \phi \) has two units of charge
Portals to the Standard Model

\[ B_{\mu\nu} V_{\mu\nu} \]  

“Kinetic mixing” with additional U(1)’ group

\[ H^+ H (\lambda S^2 + A S) \]  

Higgs-singlet scalar interactions (scalar portal)

\[ LH N \]  

neutrino Yukawa coupling, \( N - \text{RH} \) neutrino

\[ \mathcal{L}_\psi = \frac{1}{2} \left( i\bar{\chi}_1 \partial_\mu \chi_1 + i\bar{\chi}_2 \partial_\mu \chi_2 - m_{\chi_1} \bar{\chi}_1 \chi_1 - m_{\chi_2} \bar{\chi}_2 \chi_2 \right) \]

\[ + \frac{i}{2} g_X \hat{X}_\mu (\bar{\chi}_2 \gamma^\mu \chi_1 - \bar{\chi}_1 \gamma^\mu \chi_2) + \frac{f}{2} \hat{h}' (\bar{\chi}_1 \chi_1 - \bar{\chi}_2 \chi_2) , \]
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Portals to the Standard Model

Wilczek (2006)

\[ B_{\mu\nu} V_{\mu\nu} \]

\( H^+ H \left( \lambda S^2 + A S \right) \)

\[ \theta \]

scalar mixing angle

\[ \mathcal{L}_\psi = \frac{1}{2} \left( i \bar{\chi}_1 \hat{\phi} \chi_1 + i \bar{\chi}_2 \hat{\phi} \chi_2 - m_{\chi_1} \bar{\chi}_1 \chi_1 - m_{\chi_2} \bar{\chi}_2 \chi_2 \right) \]

\[ + \frac{i}{2} g X \hat{X}_\mu (\bar{\chi}_2 \gamma^\mu \chi_1 - \bar{\chi}_1 \gamma^\mu \chi_2) + \frac{f}{2} \hat{h}' (\bar{\chi}_1 \chi_1 - \bar{\chi}_2 \chi_2) \]
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**Portals to the Standard Model**

Wilczek (2006)

\[ B_{\mu\nu} V_{\mu\nu} \]

\[ H^+ H (\lambda S^2 + A S) \]

\[ LHN \]

“Kinetic mixing” with additional U(1)' group

Higgs-singlet scalar interactions (scalar portal)

neutrino Yukawa coupling, \( N – RH \) neutrino

**two portal model**

\[
\mathcal{L}_\psi = \frac{1}{2} \left( i \chi_1 \phi \chi_1 + i \chi_2 \phi \chi_2 - m_{\chi_1} \chi_1 \chi_1 - m_{\chi_2} \chi_2 \chi_2 \right)
\]

\[ + \frac{i}{2} g x \hat{X}_\mu (\chi_2 \gamma^\mu \chi_1 - \chi_1 \gamma^\mu \chi_2) + \frac{f}{2} \hat{h}'(\chi_1 \chi_1 - \chi_2 \chi_2), \]

Inelastic interactions  Elastic interactions
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Relic density via thermal processes

$p$-wave
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Relic density via thermal processes

Elastic Scattering

$\chi_1 \rightarrow \h_1 \h_1$

$p$-wave

$\chi_1 \rightarrow \h_1$

suppressed
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Relic density via thermal processes

Elastic Scattering

More parameter space

$p$-wave

$\superscript{suppressed}$

Rich phenomenology

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Displaced Vertices involving the Higgs

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Dark Photon Plane

\[ m_{A'} = 4m_{\chi_1} \]
\[ m_{h'} = 1 \text{GeV} \]
\[ \theta = 10^{-5}, \Delta = m_{\chi_1} \]
\[ \alpha_D = 0.1 \]

BaBar mono-\( \gamma \)

Thermal relic

\[ \epsilon \]

Preliminary
Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg

\[ m_{A'} = 4m_{\chi_1} \]
\[ m_{h'} = 1 \text{GeV} \]
\[ \theta = 10^{-5}, \Delta = m_{\chi_1} \]
\[ \alpha_D = 0.5 \]

\[ \epsilon \]

Inelastic DM and a Dark Higgs

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Inelastic DM and a Dark Higgs

Preliminary

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Preliminary

\( \epsilon = 10^{-3} \quad \theta = 10^{-5} \quad m_{A'} = 4m_{X_1} \)
\( \alpha_D = 0.1 \quad \alpha_f = 0.006 \quad (\Delta = m_{X_1}) \)

\( m_{A'} = 4m_{X_1} = 10 \text{ GeV} \)
\( \theta = 10^{-5} \quad \epsilon = 10^{-3} \quad \alpha_D = 0.1 \)

\( \Delta/m_{X_1} \)

**CMB**

\( m_{A'} \) (GeV)

\( m_{X_1} \) (GeV)

\( \Delta/m_{X_1} \)
Conclusions

Inelastic DM is a well-motivated thermal DM candidate at the subGeV scale, in which a mass splitting between dark matter and its excited state allows to evade stringent CMB bounds and direct detection limits.

I discussed the phenomenological impact of including a dark Higgs to generate the mass splitting and the dark photon mass.

I have investigated the sensitivity of Belle II for the key signature of this model: a lepton pair originating from a displaced vertex in association with a single photon as well as with a dark Higgs.

Preliminary Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg