Multi-component vector-fermion dark matter with scalar mediator

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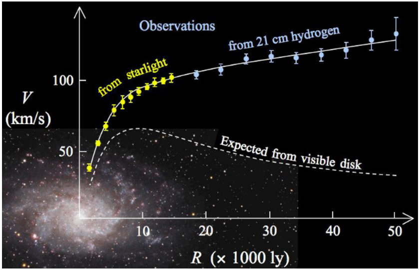
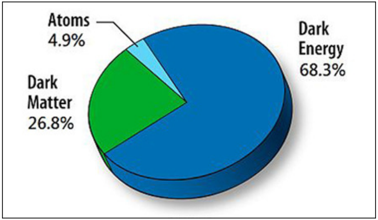
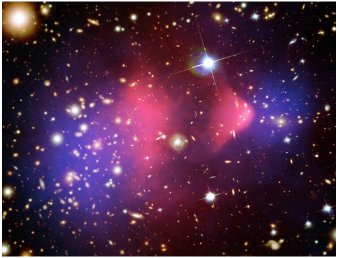
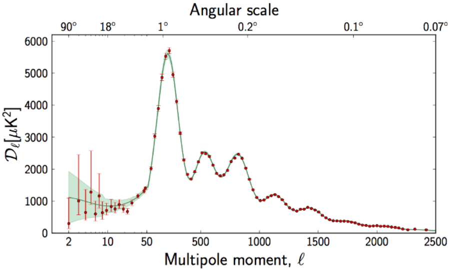
Aqeel Ahmed, MD, Bohdan Grzadkowski, Michal Iglicki
Multi-component Dark Matter: the vector and fermion case [1710.01853]





Convicing evidence on various astrophysical and cosmological scales

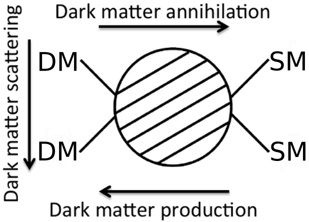




Motivation – Dark Matter

Properties of dark matter:

- electrically neutral (non luminous)
- non-relativistic (cold) (structure formation)
- stable or long-lived
- weakly interacting with ordinary matter



Experimental probes

- annihilation – indirect detection (FERMI-LAT, MAGIC, H.E.S.S, ...)
- production – collider searches
- scattering on nucleons – direct detection (LUX, XENON, PANDA, ...)

Strong bounds on many models and inconclusive detection signals

Stability

Lightest particle transforming non-trivially under a given symmetry

Lesson from the Standard Model

- globally charged particles (accidental symmetry) - proton
- locally charged particles (gauge symmetry) - electron
- lightest fermion (Poincare symmetry) - neutrino

Simplest DM realization – Z_2 symmetry

Production mechanism

- pair annihilation of DM particles
- freeze-out when annihilation rate $\Gamma_{ann} < H$

SM is rich $\Rightarrow$ dark sector can also consist of various particles

Additional gauge symmetry in the hidden sector

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathbf{U(1)_X}$$

- SM states are singlets of $\mathbf{U(1)_X}$
- dark sectors states are singlets of the SM gauge group
- fermion with dark charge $1/2$
- complex scalar with dark charge 1
- masses in the hidden sector are generated via spontanous symmetry breaking of $U(1)_X$
- dark fermion and vector are DM candidates

Non-Abelian gauge group (vector – scalar DM case)

Arcadi, Gross, Lebedev, Mambrini, Pokorski, Toma [1611.00365]

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\mathrm{portal}}$$

- Dark sector Lagrangian is

$$\mathcal{L}_{\mathrm{DM}} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \left(\mathcal{D}_\mu S\right)^* \mathcal{D}^\mu S + \mu_S^2 |S|^2 - \lambda_S |S|^4 + \bar{\chi}\left(i\not{\mathcal{D}} - m_D\right)\chi - \frac{1}{\sqrt{2}}\left(y_{\mathrm{X}} S^* \chi^{\intercal} \mathcal{C} \chi + \mathrm{H.c.}\right),$$

where $D_\mu = \partial_\mu + i g_x X_\mu$ with gauge coupling g_x.

- Connection to the SM (Higgs portal)

$$\mathcal{L}_{\mathrm{portal}} = -\kappa |S|^2 |H|^2$$

- Kinetic mixing $\cancel{B^{\mu\nu} X_{\mu\nu}}$ forbidden by charge conjugation symmetry $\mathcal{C}$

$$X_\mu \xrightarrow{\mathcal{C}} -X_\mu, \quad S \xrightarrow{\mathcal{C}} S^*, \quad \chi \xrightarrow{\mathcal{C}} \chi^c \equiv -i\gamma_2 \chi^*$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\pi^+ \\ v + h + i\pi^0 \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} (v_x + \phi + i\sigma)$$

$$\begin{aligned}\mathcal{L}_{\rm DM} =& \frac{i}{2} (\bar{\psi}_+ \gamma^\mu \partial_\mu \psi_+ + \bar{\psi}_- \gamma^\mu \partial_\mu \psi_-) - \frac{1}{2} m_+ \bar{\psi}_+ \psi_+ - \frac{1}{2} m_- \bar{\psi}_- \psi_- \\ &- \frac{i}{4} g_x (\bar{\psi}_+ \gamma^\mu \psi_- - \bar{\psi}_- \gamma^\mu \psi_+) X_\mu - \frac{y_{\rm X}}{2} (\bar{\psi}_+ \psi_+ - \bar{\psi}_- \psi_-) \phi\end{aligned}$$

Two scalar mediators

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

$M_{h_1} = 125$ GeV

Massive vector boson $M_{Z'} = g_x v_x$

Two dark Majorana fermions

$$\psi_+ \equiv \frac{1}{\sqrt{2}} (\chi + \chi^c)$$

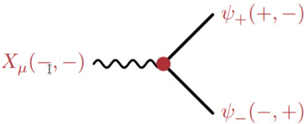
$$\psi_- \equiv \frac{1}{i\sqrt{2}} (\chi - \chi^c)$$

$$m_\pm = m_D \pm y v_x .$$

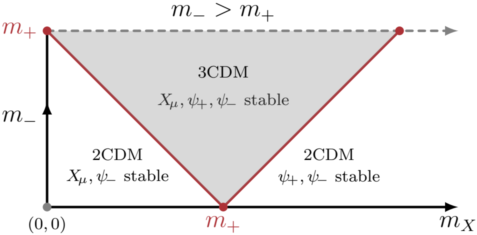
Symmetries and stability

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\left(\bar{\psi}_+\gamma^\mu\partial_\mu\psi_+ + \bar{\psi}_-\gamma^\mu\partial_\mu\psi_-\right) - \frac{1}{2}m_+\bar{\psi}_+\psi_+ - \frac{1}{2}m_-\bar{\psi}_-\psi_-$$
$$- \frac{i}{4}g_x\left(\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+\right)X_\mu - \frac{y_{\rm X}}{2}\left(\bar{\psi}_+\psi_+ - \bar{\psi}_-\psi_-\right)\phi$$

Symmetry	X_μ	ψ_+	ψ_-	ϕ
Z_2	$-$	$+$	$-$	$+$
Z_2'	$-$	$-$	$+$	$+$
Z_2''	$+$	$-$	$-$	$+$



ψ_- is always stable



- $m_+ > m_- + m_X$
- $m_X > m_+ + m_-$
- $m_+ + m_- > m_X > m_+ - m_-$

Boltzmann equations for 2(3)-component DM

$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma^{XX\phi\phi'}_{v_{\text{Møl}}}\rangle \left(n_X^2 - \bar{n}_X^2\right)$$ **standard annihilation**

$$- \langle\sigma^{XX\psi_+\psi_+}_{v_{\text{Møl}}}\rangle \left(n_X^2 - \bar{n}_X^2 \frac{n_{\psi_+}^2}{\bar{n}_{\psi_+}^2}\right) - \{\psi_+ \Rightarrow \psi_-\}$$ **conversions**

$$- \langle\sigma^{X\psi_+\psi_- h_i}_{v_{\text{Møl}}}\rangle \left(n_X n_{\psi_+} - \bar{n}_X \bar{n}_{\psi_+} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}}\right) - \{\psi_+ \Leftrightarrow \psi_-\} - \{\psi_+ \Leftrightarrow h_i\}$$ **semi(co)-annihilation**

$$+ \Gamma_{\psi_+ \to X\psi_-} \left(n_{\psi_+} - \bar{n}_{\psi_+} \frac{n_X}{\bar{n}_X} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}}\right),$$ **decays**

$$\frac{dn_{\psi_-}}{dt} = -3Hn_{\psi_-} - \langle\sigma^{\psi_-\psi_-\phi\phi'}_{v_{\text{Møl}}}\rangle \left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2\right)$$ **standard annihilation**

$$- \langle\sigma^{\psi_-\psi_- XX}_{v_{\text{Møl}}}\rangle \left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2 \frac{n_X^2}{\bar{n}_X^2}\right) - \{\psi_-\psi_- \Rightarrow XX\}$$ **conversions**

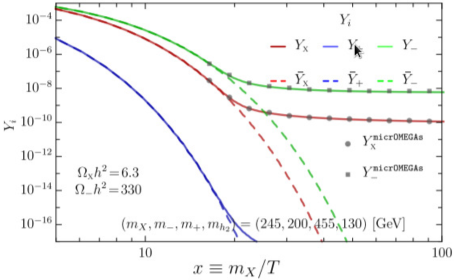
$$- \langle\sigma^{\psi_- X\psi_+ h_i}_{v_{\text{Møl}}}\rangle \left(n_{\psi_-} n_X - \bar{n}_{\psi_-} \bar{n}_X \frac{n_{\psi_+}}{\bar{n}_{\psi_+}}\right) - \{X \Leftrightarrow \psi_+\} - \{X \Leftrightarrow h_i\}$$ **semi(co)-annihilation**

$$+ \Gamma_{\psi_+ \to X\psi_-} \left(n_{\psi_+} - \bar{n}_{\psi_+} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}} \frac{n_X}{\bar{n}_X}\right),$$ **decays**

$$\frac{dn_{\psi_+}}{dt} = \text{analogous to } \psi_-$$

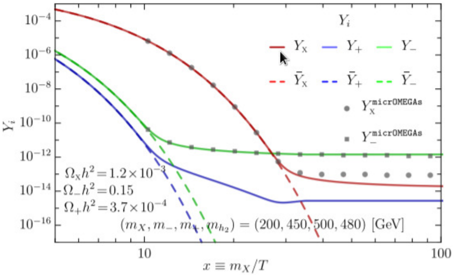
2-component scenario

$\sin\alpha = 0.2,\ g_X = 0.1,\ \lambda_H \simeq 0.128,\ \lambda_S \simeq 0.001,\ \kappa \simeq -4\times 10^{-4},\ y_X \simeq 0.05$



3-component scenario

$\kappa = 1,\ \sin\alpha = 0.3,\ g_X = 0.8,\ \lambda_H = 0.29,\ \lambda_S = 1.7,\ y = 0.1$



- We solve the Boltzmann equations using our C++ code which employs CalcHEP to calculate matrix elements.
- Within 2-component models it agrees with micrOMEGAs.
- The presence of the third component can alter evolution of others.

- Multicomponent models are a viable scenario of DM
- Imposing gauge symmetry in the model with dark scalar and fermion leads to a 2(3)-component DM which exhibits complexity of multicomponent scenarios
- DM Pair annihilation is not enough to set the relic abundance in the hidden sector (semi(co)-annihilations, conversions)
- We developed a dedicated C++ code to solve the Boltzmann equation