Z_p scalar dark matter from multi-Higgs-doublet models

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Dark matter Stability

DMs must be (almost) stable on cosmological time-scales

The simplest way to guarantee stability is to devise a model with completely inert dark matter, which would not be destroyed in any reaction, and would only annihilate through $dd^* \to X_{SM}$

d: dark matter, d^*: dark matter anti-particle, X_{SM}: any set of SM particles

In many models the stability is associated with a conserved Z_2 quantum number;
In Supersymmetric models: R-parity
In phenomenological models (IDM, MSM): imposed Z_2 symmetry on the Lagrangian

Groups larger than Z_2

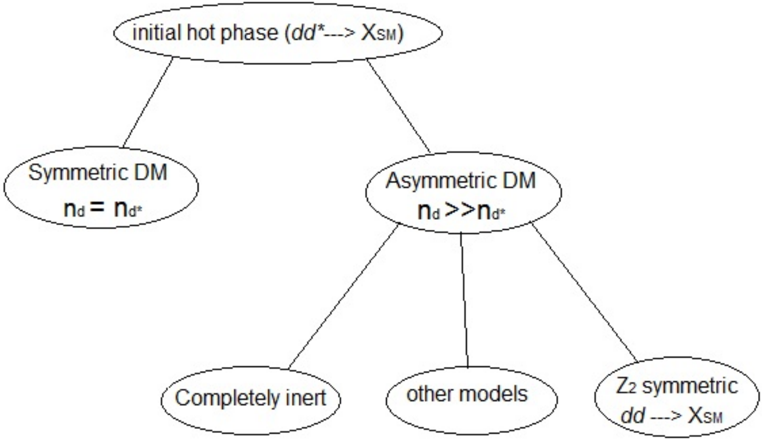
Although Z_2 symmetric models avoid the decay of d to Standard Model particles, they allow direct two-particle annihilation $dd \to X_{SM}$, which changes the kinetics of dark matter evolution in the early Universe and its relic abundance after the freeze-out

To avoid the direct two-particle annihilation, it is natural to explore groups larger than Z_2

One particular class of groups used to stabilize DM are cyclic groups Z_p, where all fields are characterized by a conserved quantum number q

All the SM fields including the SM-like Higgs boson; $q = 0$
The dark matter candidates; $q \neq 0$

Our work


initial hot phase (dd*---> XSM)
Symmetric DM
nd = nd*
Asymmetric DM
nd >> nd*
Completely inert
other models
Z2 symmetric
dd ---> XSM

Abelian symmetries in multi-Higgs-doublet models

Our recent work completely characterized all realizable Abelian groups of the Higgs-family transformations and generalized CP-transformations [I. P. Ivanov, V. Keus, E. Vdovin, J Phys. A 45, 215201 (2012)]

Cyclic group Z_p with any $1 < p \leq 2^{N-1}$ is realizable for NHDM

We show that Z_p stabilized scalar DM can arise in multi-Higgs-doublet models (NHDM)

The advantage of these models is that even with few doublets one can get Z_p with a rather large p

An EWSB model with Z_p-stabilized scalar dark matter must satisfy several conditions:

• The entire Lagrangian and not only the Higgs potential must be Z_p-symmetric: set the Z_p charges of all SM particles to zero and require that only one Higgs doublet (the SM-like doublet) couples to fermions

• The Z_p symmetry must remain after EWSB: only SM-like doublet acquires a no-zero v.e.v.

• Z_p-stabilization: not only decays but also 2-, 3-, . . . , $(p-1)$-particle annihilation to SM fields are forbidden by quantum number conservation, then the dark matter candidates must have Z_p charge q which is co-prime with p.

NHDMs can easily satisfy these conditions

Z_3 symmetric 3HDM

We start with a simple model of Z_3-symmetric 3HDM

Scalar potential invariant under G of phase rotations can be written as
$V = V_0 + V_G$
where V_0 is invariant under any phase rotation, and V_G is a collection of extra terms which realize the chosen symmetry group

The generic phase-rotation-invariant part:

$$V_0 = \sum_i \left[-m_i^2 (\phi_i^\dagger \phi_i) + \lambda_{ii} (\phi_i^\dagger \phi_i)^2 \right] + \sum_{ij} \left[\lambda_{ij} (\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij} (\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]$$

Z_3 symmetric 3HDM

And the Z_3 symmetric part:

$$V_{Z_3} = \lambda_1(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_1) + \lambda_2(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_2) + \lambda_3(\phi_2^\dagger\phi_3)(\phi_1^\dagger\phi_3) + h.c.$$

Which is symmetric under the phase rotations generated by;

$$\phi_1 \to \phi_1 \quad , \quad \phi_2 \to e^{2i\pi/3}\phi_2 \quad , \quad \phi_3 \to e^{4i\pi/3}\phi_3$$

The vector of phases: $a = \frac{2\pi}{3}(0,\, 1,\, 2)\,, \quad a^3 = 1$

We chose ϕ_1 to be the SM-like doublet

To conserve the symmetry: $\langle\phi_1^0\rangle = \frac{v}{\sqrt{2}},\ \langle\phi_2^0\rangle = \langle\phi_3^0\rangle = 0$

Z_3 symmetric 3HDM

We now pick a simple version of the model:

$$\begin{aligned} V = \quad & -m_1^2(\phi_1^\dagger\phi_1) + |m_2^2|(\phi_2^\dagger\phi_2) + |m_3^2|(\phi_3^\dagger\phi_3) \\ & +\lambda_0\left[(\phi_1^\dagger\phi_1)^2 + (\phi_2^\dagger\phi_2)^2 + (\phi_3^\dagger\phi_3)^2\right] \\ & +\lambda_1(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_1) + \lambda_2(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_2) + \lambda_3(\phi_2^\dagger\phi_3)(\phi_1^\dagger\phi_3) + h.c. \end{aligned}$$

With the global minimum at $\langle\phi_i^0\rangle = (\frac{v}{\sqrt{2}}, 0, 0)$, where $v^2 = m_1^2/\lambda_0$
In order to find the mass matrices:

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v+h+iG^0) \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} w_2^+ \\ z_2 \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} w_3^+ \\ z_3 \end{pmatrix}$$

Where h; the SM-like Higgs boson, G^0, G^+; Goldstone bosons, w_2^+, w_3^+ and z_2, z_3; charged and neutral scalar bosons

Quantum numbers

Associating Z_3 quantum numbers to the particles according to the generator $a = \frac{2\pi}{3}(0, 1, 2)$:

Field h: $q = 0$
Fields w_2^+, z_2: $q = 1$
Fields w_3^+, z_3: $q = 2$

Fields $w_2^-, z_2{}^*$: $q = -1 \quad (\equiv 2 \text{ mod } 3)$
Fields $w_3^-, z_3{}^*$: $q = -2 \quad (\equiv 1 \text{ mod } 3)$

Therefore neutral complex fields z_2 and z_3^* can mix, leading to two mass eigenstates d and D

Mass eigenstates

$m_h^2 = 2m_1^2$

$m^2_{w_2^\pm} = |m_2^2|$ and $m^2_{w_3^\pm} = |m_3^2|$

Neutrals with equal q can mix, resulting mass eigenstates d and D $(m_d < m_D)$:

$$d = \cos\alpha z_2 + \sin\alpha e^{-i\beta} z_3^*, \quad D = -\sin\alpha e^{i\beta} z_2 + \cos\alpha z_3^*$$

$$m^2_{D,d} = \frac{|m_2^2| + |m_3^2|}{2} \pm \frac{1}{2}\sqrt{(|m_2^2| - |m_3^2|)^2 + \frac{|\lambda_1|^2}{\lambda_0^2} m_1^4}$$

Mass spectrum

$$m_d < m_{w_2^\pm}, m_{w_3^\pm} < m_D \quad , \quad m^2_{w_2^\pm} + m^2_{w_3^\pm} = m_d^2 + m_D^2$$

Interactions

The triple and quadratic interactions in the potential specify the dynamics of the DM candidate
Lightest particle is d and is stabilized by the Z_3 symmetry

The main process leading to depletion of DM is the direct annihilation $dd^* \to X_{SM}$

In the case of asymmetric DM, certain concentration of d is left behind

The two-particle process $dd \to X_{SM}$ is avoided

But a new two-particle process such as $dd \to d^* X_{SM}$ is now possible (semi-annihilation), which depending on the coefficients can be as efficient as the direct annihilation, or can be suppressed by small coupling constants

Avoiding semi-annihilation in 4HDM

Terms responsible for semi-annihilation, $dd \to d^* X_{SM}$, were due to the Z_3 symmetry group

It is possible to avoid this process by employing a Z_p group with larger p

Recall that any group Z_p with $p \leq 8$ is realizable in 4HDM

Z_p groups in 4HDM

Cyclic groups realizable as symmetry groups in the scalar sector of 4HDM;

group	interaction terms	phase rotations
Z_2	$(1^\dagger 2),\ (1^\dagger 3),\ (1^\dagger 4)^2$	$\frac{2\pi}{2}(0,\ 0,\ 0,\ 1)$
Z_3	$(3^\dagger 2),\ (1^\dagger 3)(4^\dagger 3),\ (1^\dagger 4)(1^\dagger 2)$	$\frac{2\pi}{3}(0,\ 1,\ 1,\ 2)$
Z_4	$(3^\dagger 2),\ (1^\dagger 3)(4^\dagger 3),\ (1^\dagger 4)^2$	$\frac{2\pi}{4}(0,\ 1,\ 1,\ 2)$
Z_5	$(4^\dagger 3)(2^\dagger 3),\ (3^\dagger 2)(1^\dagger 2),\ (4^\dagger 1)(3^\dagger 1)$	$\frac{2\pi}{5}(0,\ 1,\ 2,\ 3)$
Z_6	$(4^\dagger 3)(2^\dagger 3),\ (3^\dagger 2)(1^\dagger 2),\ (1^\dagger 4)^2$	$\frac{2\pi}{6}(0,\ 1,\ 2,\ 3)$
Z_7	$(4^\dagger 1)(3^\dagger 1),\ (4^\dagger 3)(2^\dagger 3),\ (4^\dagger 2)(1^\dagger 2)$	$\frac{2\pi}{7}(0,\ 2,\ 3,\ 4)$
Z_8	$(4^\dagger 3)(2^\dagger 3),\ (4^\dagger 2)(1^\dagger 2),\ (1^\dagger 4)^2$	$\frac{2\pi}{8}(0,\ 2,\ 3,\ 4)$

Z_7 symmetric 4HDM

A Z_7-symmetric 4HDM with $V = V_0 + V_{Z_7}$:

$$V_{Z_7} = \lambda_1(\phi_4^\dagger\phi_1)(\phi_3^\dagger\phi_1) + \lambda_2(\phi_4^\dagger\phi_2)(\phi_1^\dagger\phi_2) + \lambda_3(\phi_4^\dagger\phi_3)(\phi_2^\dagger\phi_3) + h.c.$$

With generator: $a = \frac{2\pi}{7}(0,\ 2,\ 3,\ 4)$

Assuming; only the first doublet couples to fermions and the global minimum at $(\frac{v}{\sqrt{2}}, 0, 0, 0)$
Expanding the doublets;

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \phi_2 = \begin{pmatrix} w_2^+ \\ z_2 \end{pmatrix}, \phi_3 = \begin{pmatrix} w_3^+ \\ z_3 \end{pmatrix}, \phi_4 = \begin{pmatrix} w_4^+ \\ z_4 \end{pmatrix}$$

Quantum numbers

Assigning quantum numbers according to $a = \frac{2\pi}{7}(0, 2, 3, 4)$:
Neutral scalars:

Field h: $q = 0$
Field z_2: $q = 2$
Field z_3: $q = 3$
Field z_4: $q = 4$

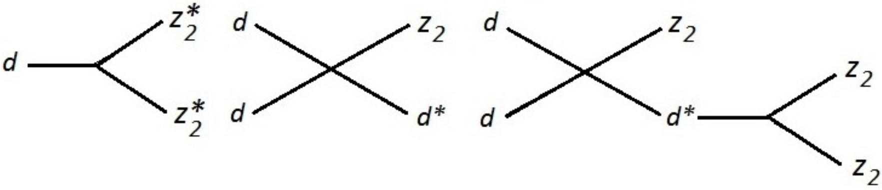
z_3 and $z_4{}^*$ mix, leading to mass eigenstates d and D

Interactions

Adjusting free parameters $\longrightarrow$ d the lightest particle (in particular $m_d < m_{z_2}$)

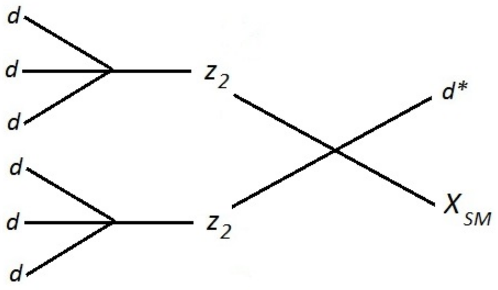
The other particles will eventually decay to d or d^* plus SM particles or will be stable, representing an additional contribution to DM

Subsequent dynamics depend on the interactions between d's and z_2's: One- or two-particle processes are kinematically forbidden



Interactions

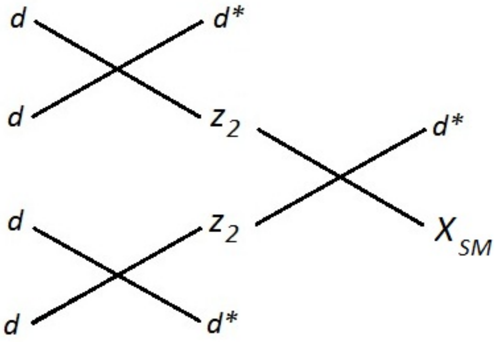
Multiple collision kinetics depend on $3m_d > m_{z_2}$



and the subsequent annihilation of d^*
The net result of this chain; $7d$-burning process, $7d \to X_{SM}$

Interactions

If $m_{z_2} > 3m_d$, one can still burn d's via the tree-level process with intermediate virtual z_2's:



Conclusion

We showed that multi-Higgs-doublet models can naturally accommodate scalar dark matter candidates protected by the group Z_p.

The advantage of these models is that even with few doublets one can get Z_p with a rather large p

These models do not require any significant fine-tuning and can lead to a variety of forms of microscopic dynamics among the dark matter candidates