Z_p scalar dark matter from multi-Higgs-doublet models

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Dark Matter (DM)

Evidence:

• Discrepancies between the mass of astronomical objects determined from their gravitational effects and what was calculates from "luminous matter"

Properties:

• Neither emits nor absorbs light or other electromagnetic radiation, must be electrically neutral

• Must provide the correct relic abundance, therefore should be stable on time scales greater than the age of the universe

Candidates:

• None of the SM particles satisfy the DM candidate conditions. We explore DM arising in BSM models, especially models that can address other particle physics issues such as EWSB

Dark matter stability

The simplest way to guarantee stability of DM is to devise a model with completely inert DM, 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 symmetry;
• Supersymmetric models: R-parity
• More phenomenologically oriented models (Inert doublet model, Minimal singlet model): 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

$$\text{"direct two-particle annihilation"} \qquad dd \to X_{SM}$$

which changes the kinetics of dark matter evolution in the early Universe and its relic abundance after the freeze-out

To avoid this process, it is natural to explore groups larger than Z_2
This idea was explored for Abelian groups
[Ma, Phys. Lett. B 662, 49 (2008)], [Batell, Phys. Rev. D 83, 035006 (2011)], [Belanger, Park, arXiv:1112.4491 [hep-ph]]
and non-Abelian finite groups
[Adulpravitchai, Batell, Pradler, Phys. Lett. B 700, 207 (2011)]

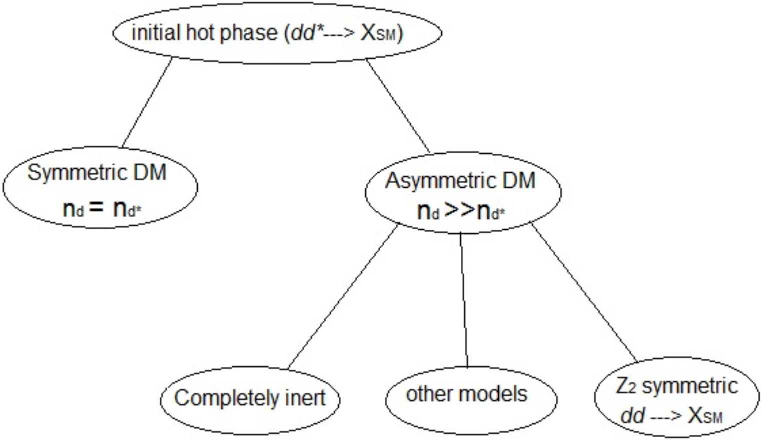
Groups Z_p with $p > 2$

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; $q \neq 0$

This strategy prohibits the direct two-particle annihilation $dd \to X_{SM}$, which would have a different impact on the kinetics of the dark mater abundances in the early Universe

Our work


initial hot phase (dd^*---> X_{SM})
Symmetric DM
$n_d = n_{d^*}$
Asymmetric DM
$n_d >> n_{d^*}$
Completely inert
other models
Z_2 symmetric
dd ---> X_{SM}

Our work

We show that N-Higgs-doublet models (NHDM) can naturally accommodate scalar DM candidates protected by 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 large variety of forms of microscopic dynamics

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

N-Higgs-doublet models

NHDMs are a conceptually simple extension of SM Higgs mechanism

Introduce N doublets of complex scalar fields ϕ_i, with electroweak isospin $Y = 1/2$

$$\phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix} \qquad i = 1, \ldots, N$$

The most general scalar potential

$$V = Y_{ij}(\phi_i^\dagger \phi_j) + Z_{ijkl}(\phi_i^\dagger \phi_j)(\phi_k^\dagger \phi_l)$$

has $N^2(N^2+3)/2$ free parameters
The explicit analysis of the most general case is impossible

Abelian symmetries in NHDM

• Showed that cyclic groups Z_p with any $1 < p \leq 2^{N-1}$ are realizable for NHDM

Example:
For 3HDM: $Z_2, Z_3, Z_4, Z_2 \times Z_2$
For 4HDM: Z_k with $k = 2, \cdots 8$, $Z_2 \times Z_k$ with $k = 2, 3, 4$, $Z_2 \times Z_2 \times Z_2$

• Introduced a method to write the most general potential that is Z_p-symmetric

• Proved that any Abelian subgroup of $SU(N)$ can be mapped onto a group of phase rotations of individual doublets

Conditions for Z_p stabilization of DM

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
- Require that only one Higgs doublet (the SM-like doublet) acquires a no-zero v.e.v and couples to fermions
- The Z_p symmetry must remain after EWSB

Z_p-stabilization:

- Dark matter candidates must have Z_p charge q which is co-prime with p
- Quantum number conservation ensures that not only decays but also 2-, 3-, . . . , $(p-1)$-particle annihilation to SM fields are forbidden

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

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:

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

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

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 (3rd order terms)

Lightest particle is d, which is stabilized by the Z_3 symmetry

From λ_1 terms: heavier particles $D \to dh$, $D \to dZ$, and $D \to w_2^+ W^-$, $D \to w_3^- W^+$ if allowed kinematically

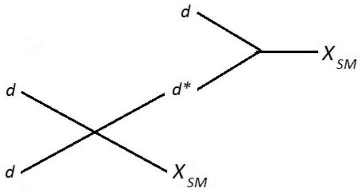
In the case of symmetric DM: the main process leading to depletion is the direct annihilation $dd^* \to X_{SM}$

For asymmetric DM: with an asymmetry between z's and z^*'s, after EWSB d's and d^*'s annihilate leaving the dark matter consisting entirely of d's

Interactions (4th order terms)

From λ_0 term: elastic scattering $dd \to dd$

From λ_2 and λ_3 terms: "semi-annihilation processes" such as $dd \to d^* X_{SM}$ with a subsequent annihilation of d^* with a d



The same interaction terms also generate the "triple annihilation processes" $ddd \to h \to X_{SM}$, whose rate is suppressed at small densities with respect to the semi-annihilation

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	$(\phi_1^\dagger\phi_2),\ (\phi_1^\dagger\phi_3),\ (\phi_1^\dagger\phi_4)^2$	$\frac{2\pi}{2}(0,0,0,1)$
Z_3	$(\phi_3^\dagger\phi_2),\ (\phi_1^\dagger\phi_3)(\phi_4^\dagger\phi_3),\ (\phi_1^\dagger\phi_4)(\phi_1^\dagger\phi_2)$	$\frac{2\pi}{3}(0,1,1,2)$
Z_4	$(\phi_3^\dagger\phi_2),\ (\phi_1^\dagger\phi_3)(\phi_4^\dagger\phi_3),\ (\phi_1^\dagger\phi_4)^2$	$\frac{2\pi}{4}(0,1,1,2)$
Z_5	$(\phi_4^\dagger\phi_3)(\phi_2^\dagger\phi_3),\ (\phi_3^\dagger\phi_2)(\phi_1^\dagger\phi_2),\ (\phi_4^\dagger\phi_1)(\phi_3^\dagger\phi_1)$	$\frac{2\pi}{5}(0,1,2,3)$
Z_6	$(\phi_4^\dagger\phi_3)(\phi_2^\dagger\phi_3),\ (\phi_3^\dagger\phi_2)(\phi_1^\dagger\phi_2),\ (\phi_1^\dagger\phi_4)^2$	$\frac{2\pi}{6}(0,1,2,3)$
Z_7	$(\phi_4^\dagger\phi_1)(\phi_3^\dagger\phi_1),\ (\phi_4^\dagger\phi_3)(\phi_2^\dagger\phi_3),\ (\phi_4^\dagger\phi_2)(\phi_1^\dagger\phi_2)$	$\frac{2\pi}{7}(0,2,3,4)$
Z_8	$(\phi_4^\dagger\phi_3)(\phi_2^\dagger\phi_3),\ (\phi_4^\dagger\phi_2)(\phi_1^\dagger\phi_2),\ (\phi_1^\dagger\phi_4)^2$	$\frac{2\pi}{8}(0,2,3,4)$

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: $q = 2$, $z_2{}^*$: $q = -2$ $(\equiv 5 \bmod 7)$
Field z_3: $q = 3$, $z_3{}^*$: $q = -3$ $(\equiv 4 \bmod 7)$
Field z_4: $q = 4$, $z_4{}^*$: $q = -4$ $(\equiv 3 \bmod 7)$

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

Mass eigenstates

$$m_h^2 = 2m_1^2$$

$$m_{z_2}^2 = m_{w_2^\pm}^2 = |m_2^2| \text{ and } m_{w_3^\pm}^2 = |m_3^2| \text{ and } m_{w_4^\pm}^2 = |m_4^2|$$

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

$$d = \cos\alpha\, z_3 + \sin\alpha e^{-i\beta}\, z_4^*\,, \quad D = -\sin\alpha e^{i\beta}\, z_3 + \cos\alpha\, z_4^*$$

$$m_{D,d}^2 = \frac{|m_3^2| + |m_4^2|}{2} \pm \frac{1}{2}\sqrt{(|m_3^2| - |m_4^2|)^2 + \frac{|\lambda_1|^2}{\lambda_0^2} m_1^4}$$

Mass spectrum

$$m_d < m_{w_3^\pm},\, m_{w_4^\pm} < m_D\,, \quad m_{w_3^\pm}^2 + m_{w_4^\pm}^2 = m_d^2 + m_D^2$$

Interactions

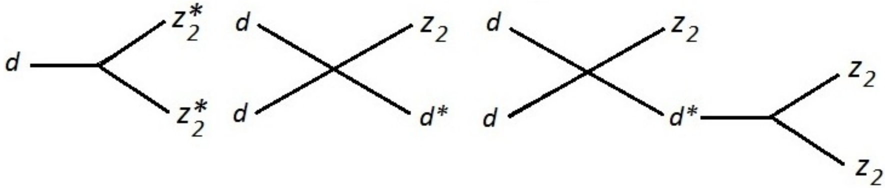
Adjusting free parameters $\Longrightarrow$ d the lightest particle (in particular $m_d < m_{z_2}$)

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

Asymmetry between d and d^* $\Longrightarrow$ after EWSB we are left predominantly with d's

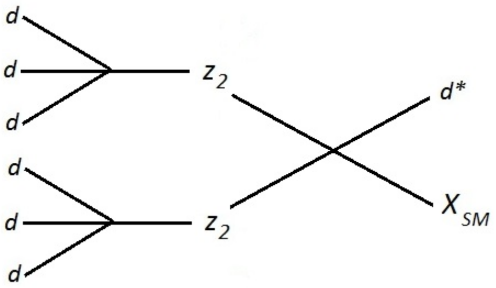
Subsequent dynamics depend on the interactions between d's and z_2's:

One- or two-particle processes are kinematically forbidden



Interactions

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

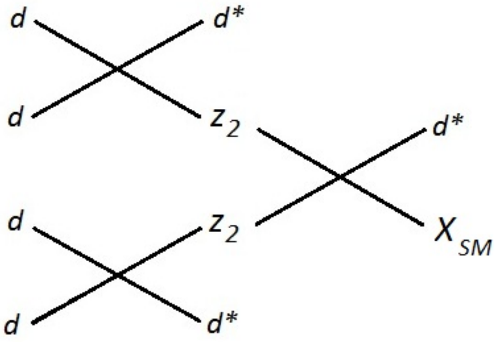


and the subsequent annihilation of d^*

The net result of this chain; $7d$-burning process, $7d \to X_{SM}$

Interactions

If $m_{z_2} > 3m_d$, then $ddd \to z_2$ is kinematically forbidden, while the inverse process leads to a quick z_2 decay. one can still burn d's via the tree-level process with intermediate virtual z_2's:



Conclusion

We showed that N-Higgs-doublet models can naturally accommodate scalar dark matter candidates protected by the group Z_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 (allowing or forbidding semi-annihilation, offering different routes to multi-particle annihilation)

Exploring the observational consequences of each sort of microscopic dynamics is a separate task