The Z_5 model of two-component dark matter

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Outline

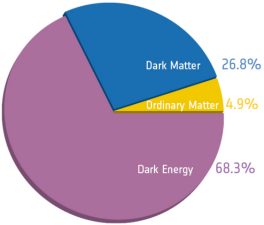
* Motivation
* The Z_5 model
* DM phenomenology
* Summary

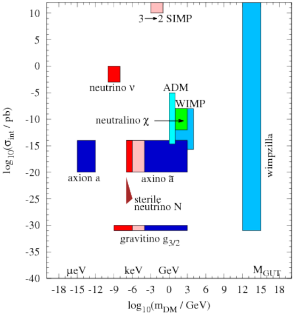
Evidence for dark matter is abundant and compelling

- Galactic rotation curves
- Bullet cluster
- Weak lensing
- Cluster and supernova data
- Big bang nucleosynthesis
- CMB anisotropies

Particle DM:

- Massive, non baryonic, elec. neutral.
- Non relativistic at decoupling.
- Stable or longlived
- $\Omega_{DM} \sim 0.25$.





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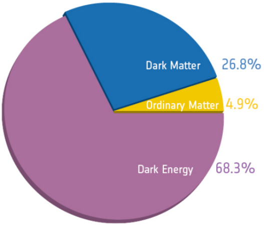

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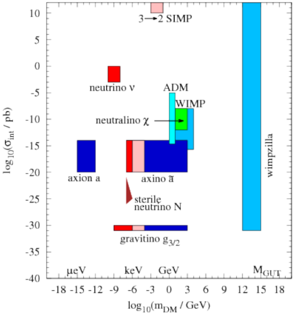

It is usually assumed that the DM is entirely explained by one single candidate ($\tilde{\chi}_1^0$, N_S, a, S, etc).

• It may be that the DM is actually composed of several species (as the visible sector): $\Omega_{DM} = \Omega_1 + \Omega_2 + ...$

• These scenarios not only are perfectly consistent with observations but often lead to testable predictions in current and future DM exps.

What is the symmetry behind the stability of these distinct particles?

Z_N multicomponent scenarios

It seems that a single Z_N is the simplest way to simultaneously stabilize several DM particles (Z_N group: comprises the N Nth roots of 1.

- Models featuring scalar fields are particularly appealing.
- For k DM particles, they require k complex scalar fields that are SM singlets but have different charges under a Z_N ($N \geq 2k$).
- The Z_N could be a remnant of a spontaneously broken $U(1)$ gauge symmetry and thus be related to gauge extensions of the SM.

The Z_5 two-component DM model

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Z_5 model: interactions

Two new complex scalar fields, $\phi_{1,2}$

$$\phi_1 \to \omega_5 \phi_1, \;\; \phi_2 \to \omega_5^2 \phi_2; \qquad \omega_5 = \exp(i2\pi/5).$$

$\phi_{1,2}$ singlets under $\mathcal{G}_{SM}$ whereas the SM particles are singlets under Z_5.

$$\mathcal{V} \supset \mu_1^2|\phi_1|^2 + \lambda_{41}|\phi_1|^4 + \lambda_{S1}|H|^2|\phi_1|^2 + \mu_2^2|\phi_2|^2 + \lambda_{42}|\phi_2|^4 + \lambda_{S2}|H|^2|\phi_2|^2$$
$$+ \lambda_{412}|\phi_1|^2|\phi_2|^2 + \frac{1}{2}\left[\mu_{S1}\phi_1^2\phi_2^* + \mu_{S2}\phi_2^2\phi_1 + \lambda_{31}\phi_1^3\phi_2 + \lambda_{32}\phi_1\phi_2^{*3} + \text{H.c.}\right],$$

$\langle\phi_{1,2}\rangle = 0$ and $M_1/2 < M_2 < 2M_1$ so that both are stable.

Set of free parameters:

$$M_i, \lambda_{Si}, \lambda_{412}, \mu_{Si}, \lambda_{3i}.$$

How do these parameters affect $\Omega_{1,2}$, shape the viable parameter space, and determine the DM observables?

DM-SM processes

$2 \to 2$ processes that can modify the relic density of ϕ_1 and ϕ_2:

ϕ_1 Processes	Type
$\phi_1 + \phi_1^\dagger \to SM + SM$	1100 A
$\phi_1^\dagger + h \to \phi_2 + \phi_2$	1022 SA
$\phi_1 + \phi_2 \to \phi_2^\dagger + h$	1220 SA
$\phi_1 + \phi_1 \to \phi_2 + h$	1120 SA
$\phi_1 + \phi_2^\dagger \to \phi_2 + \phi_2$	1222 C
$\phi_1^\dagger + \phi_1^\dagger \to \phi_2 + \phi_1$	1112 C
$\phi_1 + \phi_1^\dagger \to \phi_2 + \phi_2^\dagger$	1122 C

According to the number of SM particles ($\mathcal{N}_{SM}$):

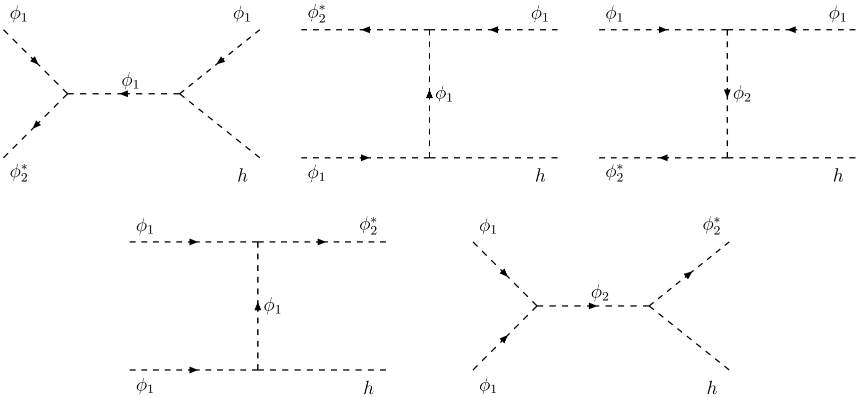
Annihilation (2), semi-annihilation (1), conversion (0).

Boltzmann eqs are solved via `micrOMEGAs 5.2.1`.

$$\frac{dn_1}{dt} = -\sigma_v^{1100}\left(n_1^2 - \bar{n}_1^2\right) - \sigma_v^{1120}\left(n_1^2 - n_2\frac{\bar{n}_1^2}{\bar{n}_2}\right) - \sigma_v^{1122}\left(n_1^2 - n_2^2\frac{\bar{n}_1^2}{\bar{n}_2^2}\right) - \frac{1}{2}\sigma_v^{1112}\left(n_1^2 - n_1 n_2\frac{\bar{n}_1}{\bar{n}_2}\right)$$
$$-\frac{1}{2}\sigma_v^{1222}\left(n_1 n_2 - n_2^2\frac{\bar{n}_1}{\bar{n}_2}\right) - \frac{1}{2}\sigma_v^{1220}\left(n_1 n_2 - n_2\bar{n}_1\right) + \frac{1}{2}\sigma_v^{2210}\left(n_2^2 - n_1\frac{\bar{n}_2^2}{\bar{n}_1}\right) - 3Hn_1.$$

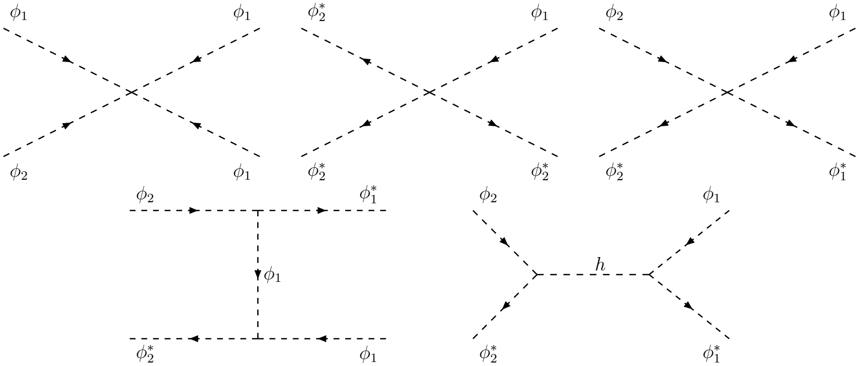
DM semi-annihilations

Semi-annihilation processes involve one μ_{S1} and one λ_{Si} :
$\phi_1\phi_2^* \to \phi_1 h$ and $\phi_2^* h \to \phi_1\phi_1$.



DM conversion processes

Conversion via (λ_{31}, λ_{32}, λ_{412}), μ_{S1}, or $\lambda_{S1} : \lambda_{S2}$.



DM annihilations proceed via the usual s-channel Higgs-mediated diagram, with W^+W^- being the dominant final state for $M_i \gtrsim M_W$.

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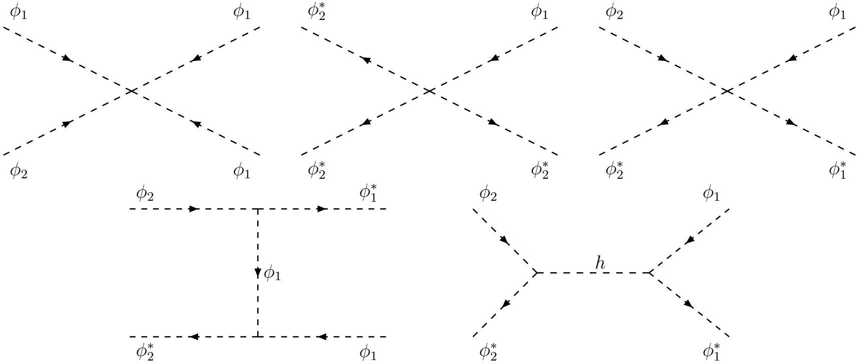

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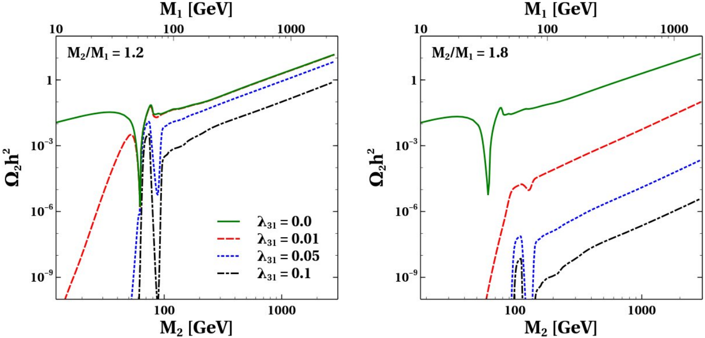
Parameter dependence

Reference model: $\mu_{Si} = 0,\ \lambda_{3i} = 0, \lambda_{412} = 0.\ \lambda_{S1} = \lambda_{S2} = 0.1.$

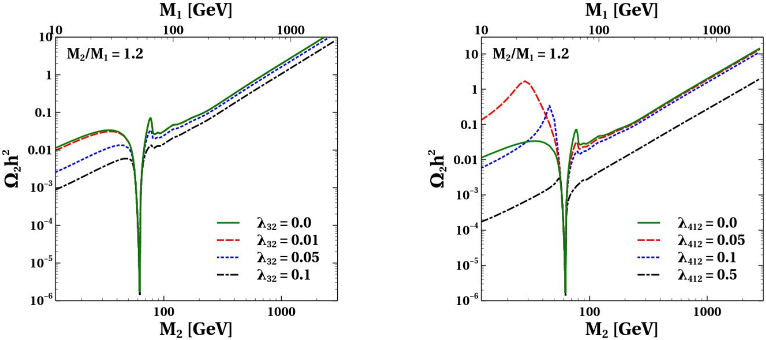
- λ_{31} only induces DM conversion processes. During the ϕ_2 freeze-out, they contribute to the depletion of ϕ_2 and therefore reduce Ω_2.
- λ_{31} as small as 10^{-2} can modify Ω_2 by several orders of magnitude.
- The larger M_2/M_1, the larger the suppression is.



- Ω_1 hardly gets modified unless $M_1 \approx M_2$, when the kinematic suppression of $\phi_1 + \phi_1 \to \phi_1^\dagger + \phi_2^\dagger$ is alleviated.

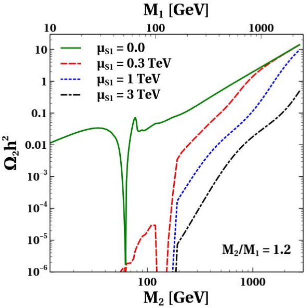
λ_{32}, λ_{412}

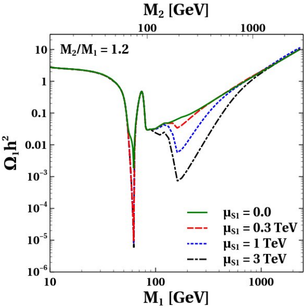
- λ_{32} leads to a reduction of Ω_2 while leaving Ω_1 mostly unaffected.
- λ_{412} causes a reduction of Ω_2 at large M_2 via $\phi_2 + \phi_2^\dagger \to \phi_1 + \phi_1^\dagger$.



- Quartic interactions affect Ω_2; the effect on Ω_1 is negligible.
- Ω_1 is determined by the Higgs-mediated interactions of the singlet scalar model. Therefore the same stringent DD constraints apply.
- The μ_{S1} and μ_{S2} can help to relax such constraints.

Trilinear interaction μ_{S1}

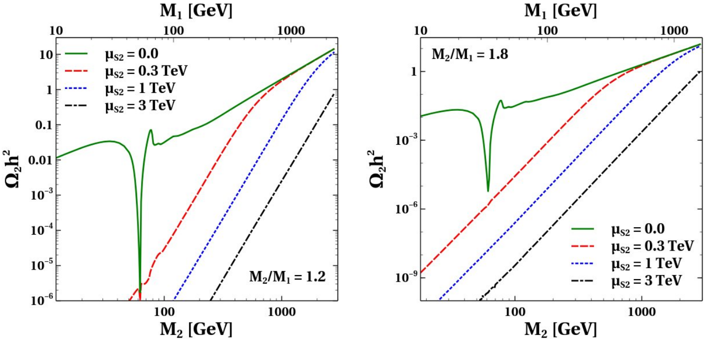




- Ω_2 can be suppressed by orders of magnitude as a consequence of the exponential suppression $\phi_1 + \phi_2^\dagger \leftrightarrow \phi_1 + h$: $dY_2/dT \propto \sigma_v^{1210} Y_1 Y_2$.
- Ω_2 increases rapidly once the process $\phi_1 + \phi_1 \to \phi_2 + h$ is kinematically open.
- At intermediate values of M_1, Ω_1 can be reduced by up to two orders of magnitude.

μ_{S2}

- μ_{S2}-induced processes can affect Ω_2 at low and intermediate masses.
- The only process that may reduce Ω_1 after ϕ_2 freeze-out is $\phi_1 + \phi_2 \to \phi_2 + h$ but it has a negligible effect on Ω_1 due to the small value of Ω_2. Exception: mass degeneracy $M_2/M_1 \lesssim 1.3$



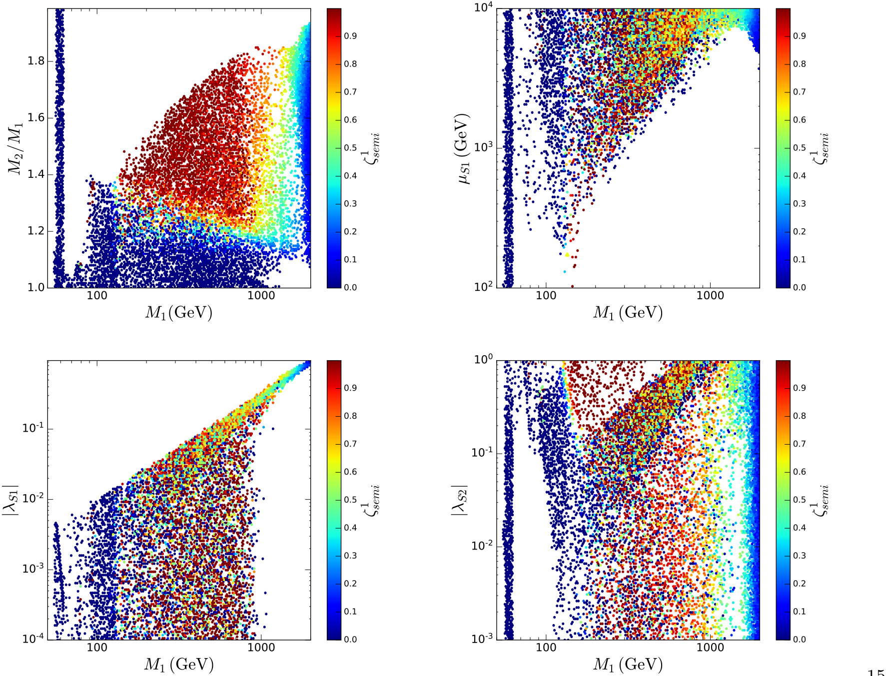
Viable parameter space

$$40\,\mathrm{GeV} \le M_1 \le 2\,\mathrm{TeV}, \quad M_1 < M_2 < 2M_1,$$
$$10^{-4} \le |\lambda_{S1}| \le 1, \quad 10^{-3} \le |\lambda_{S2}| \le 1.$$

- Scenario #1: $100\,\mathrm{GeV} \le \mu_{S1} \le 10$ TeV.
- Scenario #2: $100\,\mathrm{GeV} \le \mu_{S2} \le 10$ TeV.
- Scenario #3: $10^{-4} \le |\lambda_{3i,412}| \le 1$.

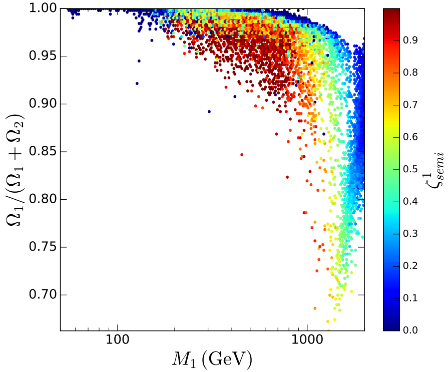
Relevance of the three kinds of processes that can contribute to Ω_1:

$$\zeta^1_{anni} \equiv \frac{\sigma_v^{1100}}{\overline{\sigma_v^1}}, \quad \zeta^1_{semi} \equiv \frac{\frac{1}{2}(\sigma_v^{1120} + \sigma_v^{1220} + \sigma_v^{1022})}{\overline{\sigma_v^1}},$$
$$\zeta^1_{conv} \equiv \frac{\sigma_v^{1122} + \sigma_v^{1112} + \sigma_v^{1222}}{\overline{\sigma_v^1}}.$$



M_2/M_1
M_1(GeV)
μ_{S1} (GeV)
M_1 (GeV)
$|\lambda_{S1}|$
M_1 (GeV)
$|\lambda_{S2}|$
M_1 (GeV)
ζ^1_{semi}

Viable parameter space

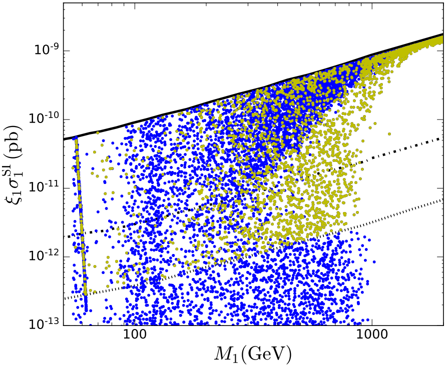


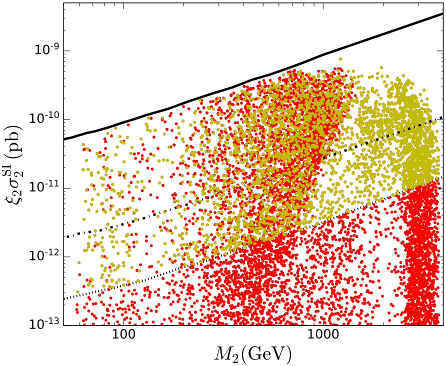
• ϕ_1 always gives the dominant contribution. It accounts for more than 70% of Ω_{DM} ($\gtrsim 95\%$ for the most points).

• In numerous cases Ω_2 turns out to be several orders of magnitude smaller than Ω_1.

Direct detection

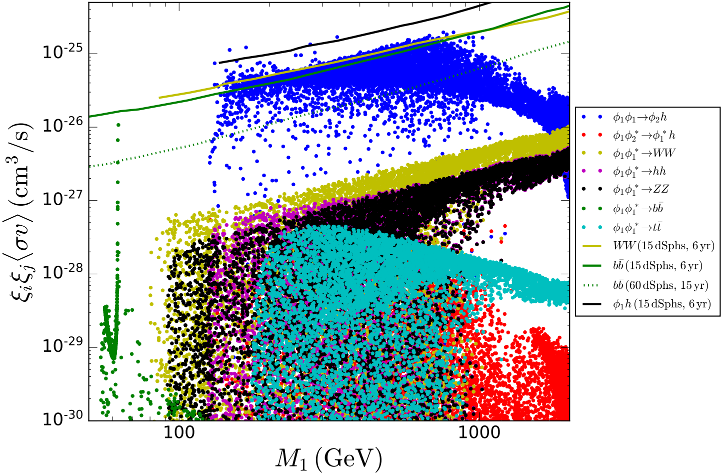
Spin-independent cross-section: $\xi_i \sigma_i^{\mathrm{SI}} = \frac{\Omega_i}{\Omega_{DM}} \frac{\lambda_{Si}^2}{4\pi} \frac{\mu_R^2 m_p^2 f_p^2}{m_h^4 M_i^2}$.





- Either DM particle may be observed in future DD experiments.
- The small Ω_2 can be compensated by a large λ_{S2}.
- Yellow points indicate that both DM particles lay within DARWIN.

If observed, such signals would rule out the *one DM paradigm*



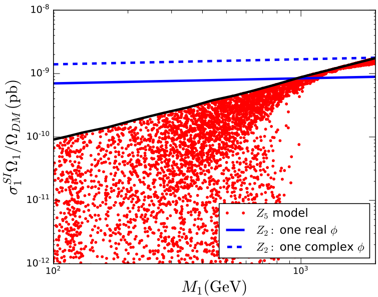
- $\phi_1\phi_1 \to \phi_2 h$ turns out to be the most relevant one $\sim 10^{-26}$cm^3/s.
- Due to the ξ_2 suppression and its higher mass, the ID signals involving ϕ_2 are less promising.

Summary

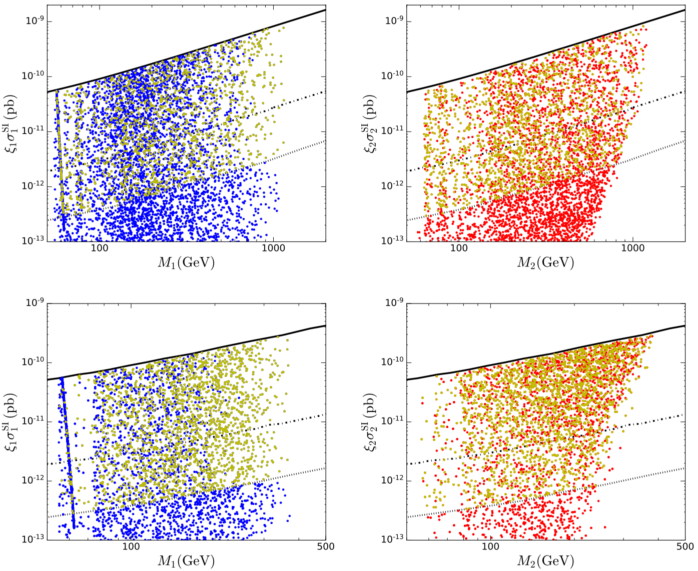
The results are essentially identical when *all* the free parameters are simultaneously varied.

1. The model becomes viable over the entire range of DM masses.
2. The lighter DM particle (ϕ_1) accounts for most of Ω_{DM}.
3. DD experiments offer great prospects to test this model, including the possibility of observing signals from *both* dark matter particles.

Besides being simple and well-motivated, the Z_5 model is a consistent and testable framework for two-component dark matter.



Result for $\mu_{S2} \neq 0$ and $\lambda_{3i,412} \neq 0$



General results

The results are essentially identical when *all* the free parameters are simultaneously varied.

1. It is possible to satisfy $\Omega \approx 0.25$ and current DD limits over the entire range of DM masses considered ($M_1 < 2$ TeV).
2. Ω_{DM} is always dominated by the lighter dark matter particle: the heavier DM particle never accounts for more than 40% and often contributes significantly less than that.
3. Either DM particle may be detected in future DD experiments.

• The results for the case $M_2 < M_1$ can be obtained by doing:
$M_1 \leftrightarrow M_2$, $\mu_{S1} \leftrightarrow \mu_{S2}$, $\lambda_{31} \leftrightarrow \lambda_{32}$, $\Omega_1 \leftrightarrow \Omega_2$, etc

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Beyond Z_5: Z_N

For $5 < N \leq 10$ with $\phi_i \sim (w_N)^i$:

- (ϕ_1, ϕ_2): all Z_N symmetries forbid the $\mu_{S2}\phi_1\phi_2^2$ and $\lambda_{31}\phi_1^3\phi_2$ terms; while the Z_7 is the only one that allows $\lambda_{32}\phi_1\phi_2^3$.
- (ϕ_2, ϕ_4): the Z_9 only allows the $\mu_{S2}\phi_2^2\phi_4^*$ interaction. The results for Z_5 apply to the Z_{10} model.

• The Z_5 model is the most general Z_N model with two complex fields, from which the DM properties for other models with a higher Z_N symmetry can be deduced to a large extent.
• The Z_7 model with (ϕ_1, ϕ_2, ϕ_3) serves as a prototype for scenarios with three DM particles.

Singlet scalar DM model

It only contains a real scalar s, singlet under the SM gauge group, but odd under a $\mathbb{Z}_2$ symmetry, which guarantees its stability.

$$V = \mu_H^2\,|H|^2 + \lambda_H\,|H|^4 + \mu_s^2\,s^2 + \lambda_s\,s^4 + \lambda_{hs}\,|H|^2\,s^2,$$