The Z_5 model of two-component dark matter

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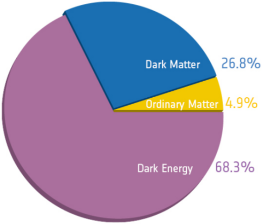
Outline

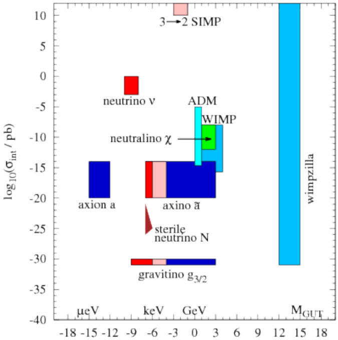
* Motivation
* The Z_5 model
* DM phenomenology
* Summary

Evidence for dark matter is abundant and compelling

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

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





Multicomponent DM

- It is often assumed that Ω_{DM} is entirely explained by one candidate ($\tilde{\chi}_1^0$, N_S, a, S, etc).
- It may also be that the DM is actually composed of several species (as the visible sector): $\Omega_{DM} = \Omega_1 + \Omega_2 + \ldots$.
- They not only are perfectly consistent with observations but often lead to testable predictions in current and future DM exps.

Who is behind the stability of DM particles?

Z_N multicomponent scenarios

- Multi-component DM models featuring scalar fields that are simultaneously stabilized by a single Z_N symmetry are particularly appealing. Z_N group: comprises the N Nth roots of 1.
- For k dark matter particles, they require k complex scalar fields that are SM singlets but have different charges under a Z_N $(N \geq 2k)$.
- This symmetry, in turn, 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

$N = 5$ is the lowest N compatible with two DM particles that are complex scalar fields.

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Z_5 model: interactions

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

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

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

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

$\langle\phi_{1,2}\rangle = 0$ and $M_1 < M_2 < 2M_1$ 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 ($\mathcal{N}_{SM}$):

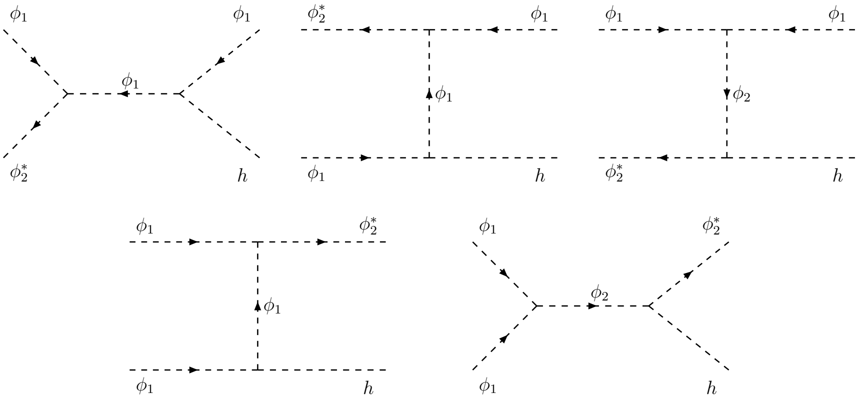
Annihilation (2), semi-annihilation (1), conversion (0).

Boltzmann eqs are solved via `micrOMEGAs 5.2.1`.

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

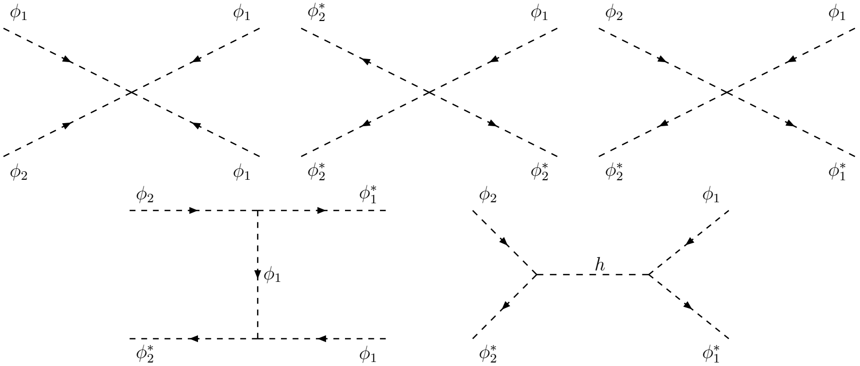
DM semi-annihilations

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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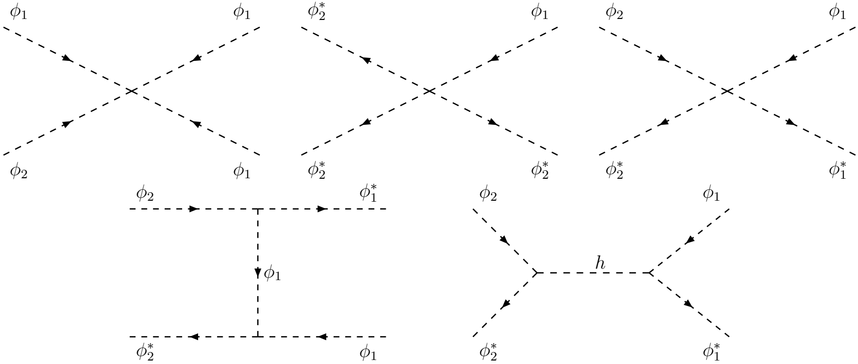

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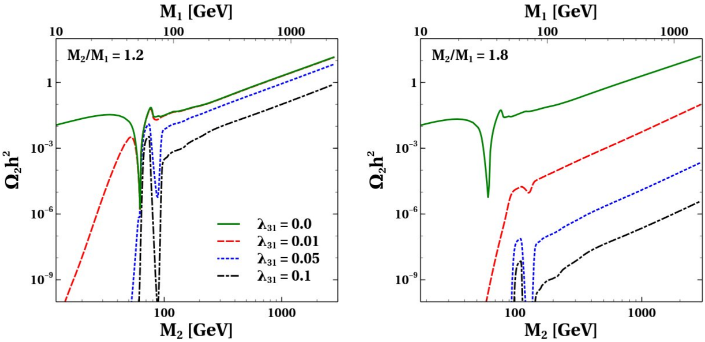
Parameter dependence

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

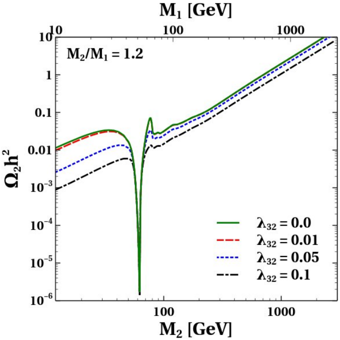
- λ_{31} only induces DM conversion processes. During the ϕ_2 freeze-out, they contribute to the depletion of ϕ_2 and therefore reduce Ω_2.
- λ_{31} as small as 10^{-2} can modify Ω_2 by several orders of magnitude.
- The larger M_2/M_1, the larger the suppression is.

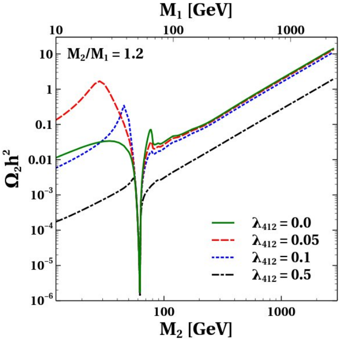


- Ω_1 hardly gets modified unless $M_1 \approx M_2$, when the kinematic suppression of $\phi_1 + \phi_1 \to \phi_1^\dagger + \phi_2^\dagger$ is alleviated.

λ_{32}, λ_{412}

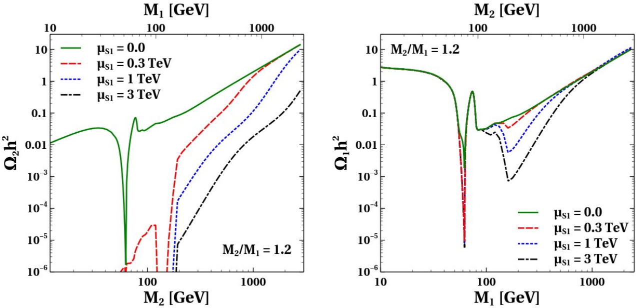
- λ_{32} leads to a reduction of Ω_2 while leaving Ω_1 mostly unaffected.
- λ_{412} causes a reduction of Ω_2 at large M_2 via $\phi_2 + \phi_2^\dagger \to \phi_1 + \phi_1^\dagger$.





- 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.

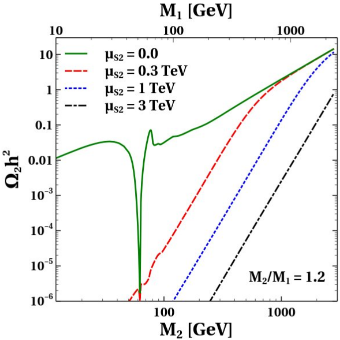
Trilinear interaction μ_{S1}

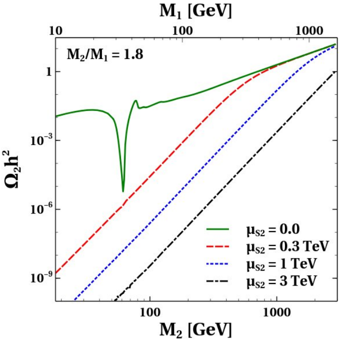


- Ω_2 can be suppressed by orders of magnitude as a consequence of the exponential suppression $\phi_1 + \phi_2^\dagger \leftrightarrow \phi_1 + h$: $dY_2/dT \propto \sigma_v^{1210} Y_1 Y_2$.
- Ω_2 increases rapidly once the process $\phi_1 + \phi_1 \to \phi_2 + h$ is kinematically open.
- At intermediate 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 $M_2/M_1 \lesssim 1.3$





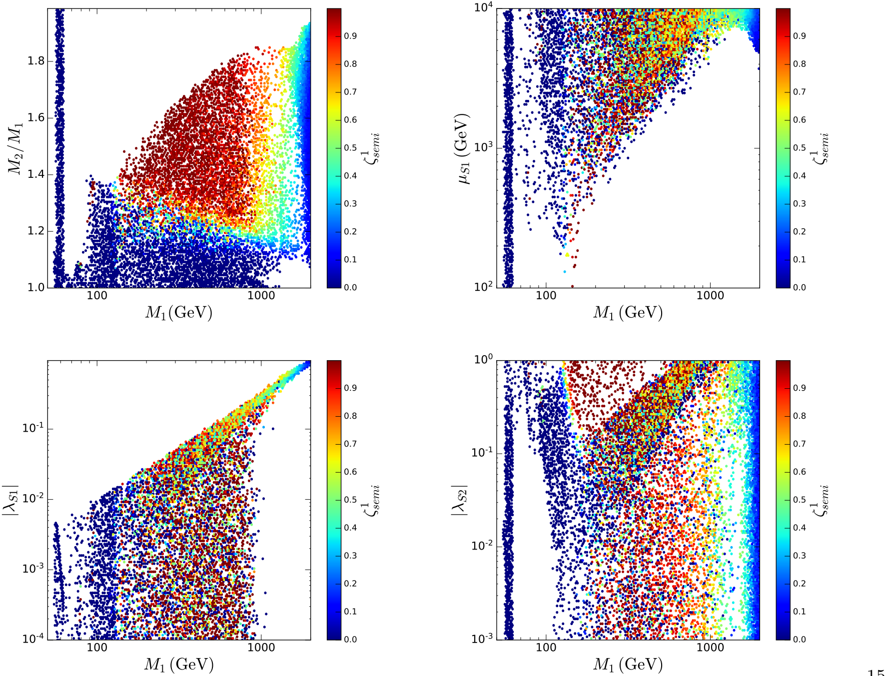
Viable parameter space

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

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

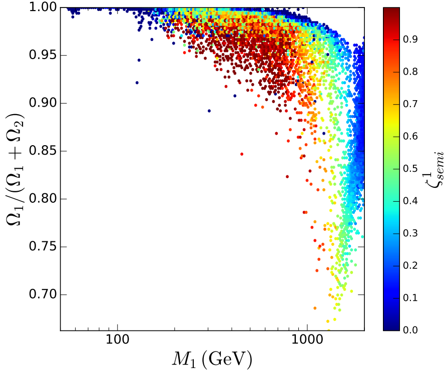
Relevance of the three kinds of processes that can contribute to Ω_1:

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



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

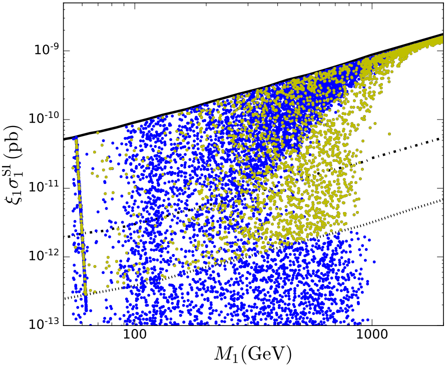


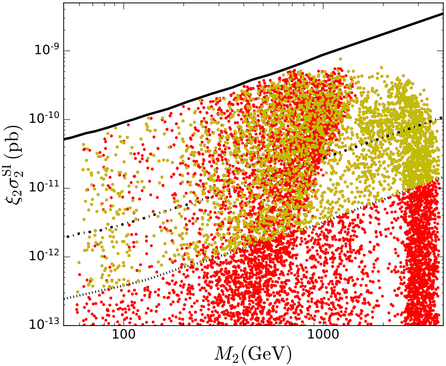
• ϕ_1 always gives the dominant contribution. It accounts for more than 70% of Ω_{DM} ($\gtrsim 95\%$ for the most points).

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

Direct detection

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

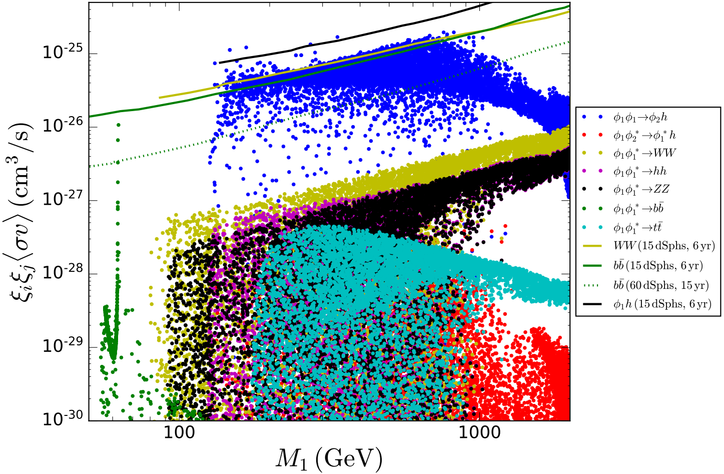




- The small Ω_2 can be compensated by a large λ_{S2}.
- Either DM particle may be observed in future DD experiments.
- Yellow points indicate that both DM particles lay within DARWIN.

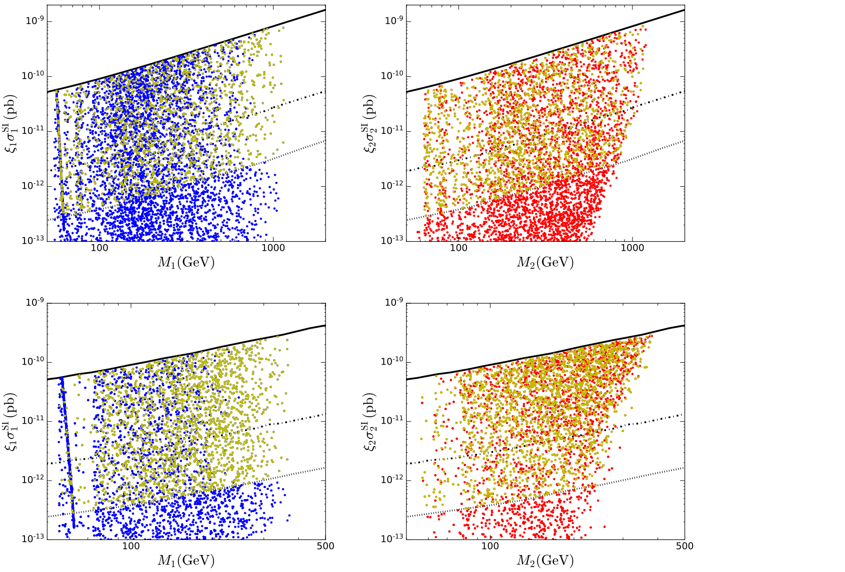
If observed, such signals would rule out the *one DM paradigm*

Indirect detection



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

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

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

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.

Summary

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.