Multicomponent dark matter: Singlet-Doublet

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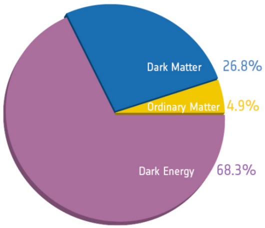
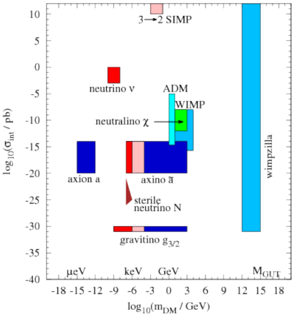
Evidence for dark matter is abundant and compelling

- 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
- $\Omega_{DM} \sim 1/4$.



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

Multicomponent DM

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

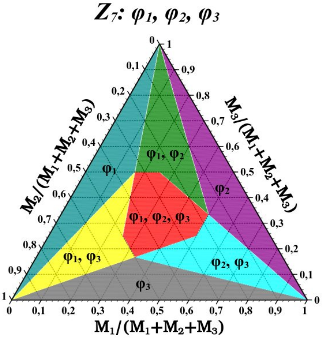
• These scenarios not only are perfectly consistent with observations but often lead to testable predictions in current and future DM exps.

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. Batel 2010, Belanger et al 2014, Yaguna & OZ 2019.

- 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.

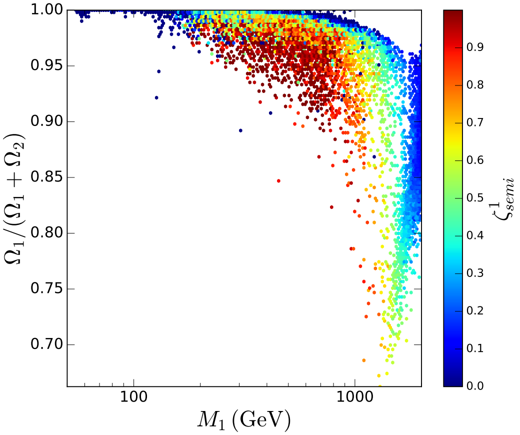


Yaguna & OZ 2019.

Two singlet complex DM fields: Z_5

Belanger, Pukhov, Yaguna & OZ JHEP2020.

1. Models with sizeable trilinear couplings (semiannihilations) become viable over the entire range of DM masses.
2. The lighter DM particle accounts for most of Ω_{DM}.



One complex ϕ_A and one real ϕ_B: Z_{2n}

$\phi_{A,B}$ singlets under $\mathcal{G}_{SM}$ ($v_{A,B} = 0$); SM is singlet under Z_{2n}.

$$\phi_A \to \omega_{2n}^m, (m < n); \qquad \phi_B \to \omega_{2n}^n = -1; \qquad \omega_{2n} = \exp(i\pi/n).$$

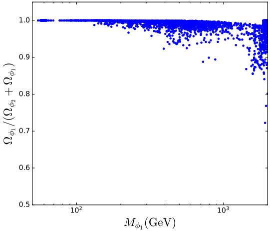
$$\mathcal{V}_{Z_{2n}}(\phi_A, \phi_B) = \mathcal{V}_1 + \mathcal{V}_2.$$

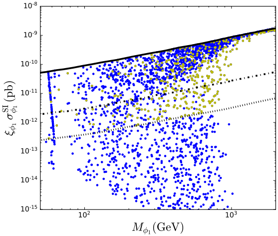
$$\begin{aligned}\mathcal{V}_1 \equiv\ & \mu_A^2 |\phi_A|^2 + \lambda_{4A} |\phi_A|^4 + \frac{1}{2}\mu_B^2 \phi_B^2 + \lambda_{4B} \phi_B^4 \\ & + \lambda_{4AB} |\phi_A|^2 \phi_B^2 + \lambda_{SA} |H|^2 |\phi_A|^2 + \frac{1}{2}\lambda_{SB} |H|^2 \phi_B^2,\end{aligned}$$

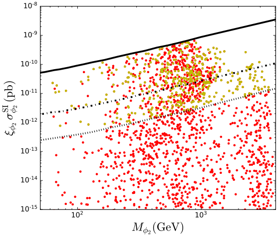
$\mathcal{V}_2$ accommodates the invariant terms associated to the specific Z_{2n} symmetry; it does not include any quadratic terms on ϕ_i.

Z_4 model

$\phi_1 \sim \omega_4, \;\; \phi_2 \sim \omega_4^2. \quad \mathcal{V}_2^{Z_4}(\phi_1, \phi_2) = \frac{1}{2}\left[\mu_{S1}\phi_1^2\phi_2 + \lambda_{51}\phi_1^4 + \text{h.c.}\right].$





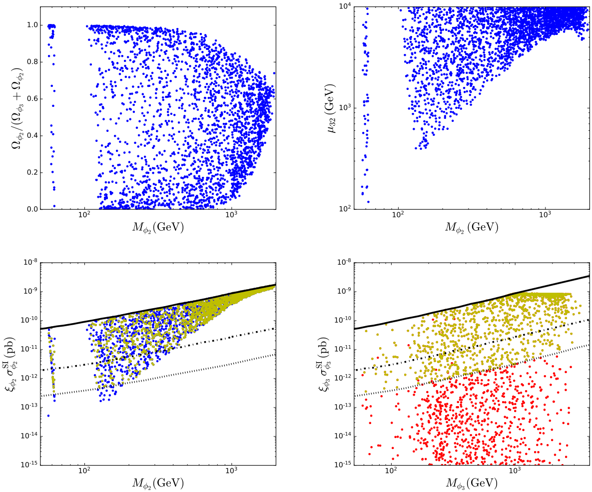


ϕ_1 always gives the dominant contribution $\gtrsim 90\%$ of Ω_{DM}.

$Z_6(23)$ model

$\phi_2 \sim \omega_6^2, \;\; \phi_3 \sim \omega_6^3. \quad \mathcal{V}_2^{Z_6}(\phi_2, \phi_3) = \frac{1}{3}\mu_{32}\phi_2^3 + \text{h.c.}.$

ϕ_2 and ϕ_3 are both stable independently of their masses.



Singlet and doublet: $Z_N\,(N \geq 4)$

- Possible interaction terms: $S\,H_2^\dagger\,H_1, \quad S^2\,H_2^\dagger\,H_1$.

$Z_N(H_2) = Z_N(S) = w_N$

$S\,H_2^\dagger\,H_1 \rightarrow$ mixing term: one single DM component.

$Z_N(S) = w_N, \qquad Z_N(H_2) = w_N^2$: complex scalar DM

$$\mathcal{L} \supset \lambda_6\,S^2\,H_2^\dagger\,H_1.$$

A special case: $N = 4$. Belanger et.al. PRD2021, JCAP2014, JCAP2012.

$Z_4(S) = w_4, \qquad Z_4(H_2) = w_4^2 = -1$:

$$\mathcal{L} \supset \lambda_6'\,S^2\,H_1^\dagger\,H_2 + \lambda_6\,S^2\,H_2^\dagger\,H_1 + \lambda_5\,(H_2^\dagger\,H_1)^2.$$

- Other charge assignments are equivalent to a $Z_2 \otimes Z_2'$ scenario.

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$S\,H_2^\dagger\,H_1 \rightarrow$ mixing term: one single DM component.

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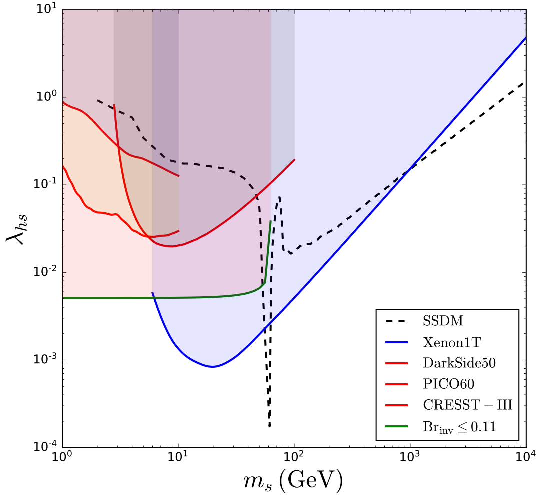
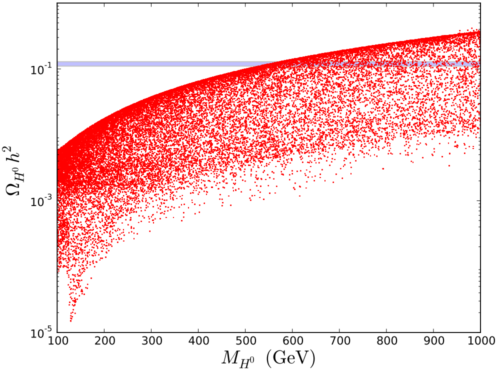
Real singlet scalar model

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



Inert doublet model

$$V \supset \mu_2^2|H_2|^2+\lambda_2|H_2|^4+\lambda_3|H_1|^2|H_2|^2+\lambda_4|H_1^\dagger H_2|^2+\frac{1}{2}\lambda_5[(H_2^\dagger H_1)^2+h.c.],$$



If $\lambda_5 = 0$: stringent DD constraints. Ruled out.

Singlet and doublet: $N \geq 5$

$$\mathcal{V}(\phi, H_2) = \mu_1^2|H|^2 + \lambda_H|H|^4 + \mu_\phi^2|\phi|^2 + \lambda_\phi|\phi|^4 + \lambda_{S1}|H_1|^2|\phi|^2$$
$$+ \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2$$
$$+ \lambda_6|H_2|^2|\phi|^2 + \frac{1}{2}\left[\lambda_7\phi^2 H_2^\dagger H_1 + \text{h.c.}\right].$$

Free parameters: $\lambda_2, \lambda_\phi, \lambda_{S1}, \lambda_L, \lambda_6, \lambda_7, M_\phi, M_{H^0}, M_{H^\pm}$.

$$H_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}.$$

$$M_\phi^2 = \mu_\phi^2 + \frac{\lambda_{S1}}{2}v^2, \qquad M_{H^\pm}^2 = \mu_2^2 + \frac{\lambda_3}{2}v^2,$$
$$M_{H^0}^2 = \mu_2^2 + \frac{(\lambda_3+\lambda_4)}{2}v^2 \equiv \mu_2^2 + \lambda_L v^2,$$

DM processes

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

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

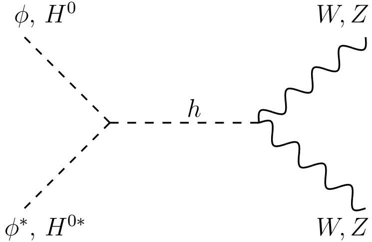
Processes that can modify the relic density of ϕ and H^0.

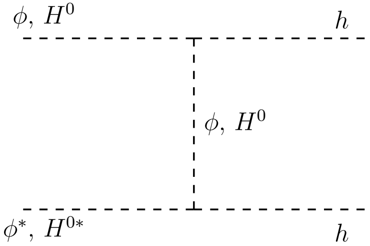
ϕ Processes	Type
$\phi + \phi^\dagger \to SM + SM$	1100
$\phi + \phi^\dagger \to H^0 + H^{0\dagger}$	1122
$\phi + \phi \to H^0 + h(Z), H^\pm + W^\mp$	1120

H^0 Processes	Type
$H^0 + H^{0\dagger} \to SM + SM$	2200
$H^0 + H^{0\dagger} \to \phi + \phi^\dagger$	2211
$H^0 + h \to \phi + \phi$	2011
$H^{0\dagger} + \phi \to \phi^\dagger + h(Z)$	2110

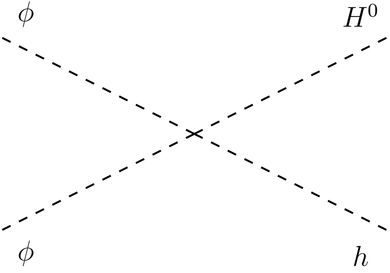
DM annihilations: Higgs portal

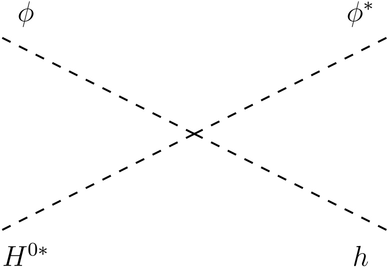
DM annihilations proceed via the usual s-channel Higgs-mediated diagram, with W^+W^- being the dominant final state for $M_{DM} \gtrsim M_W$.



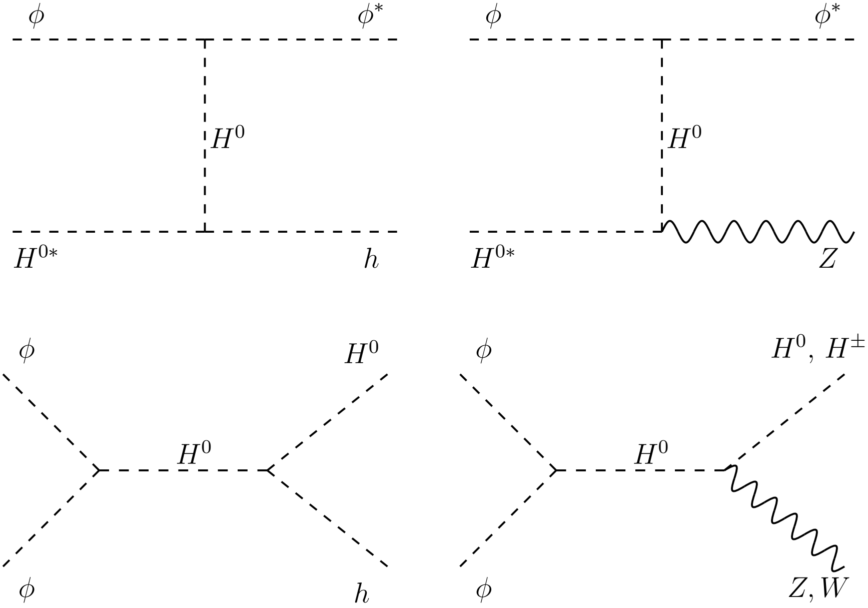


DM semiannihilations: λ_7





DM semiannihilations: Higgs, gauge and λ_7 interactions



The Boltzmann equations

$$\frac{dn_\phi}{dt} = -\sigma_v^{1100}\left(n_\phi^2 - \bar{n}_\phi^2\right) - \sigma_v^{1120}\left(n_\phi^2 - n_H\frac{\bar{n}_\phi^2}{\bar{n}_H}\right) - \sigma_v^{1122}\left(n_\phi^2 - n_H^2\frac{\bar{n}_\phi^2}{\bar{n}_H^2}\right) - 3\mathcal{H}n_\phi,$$

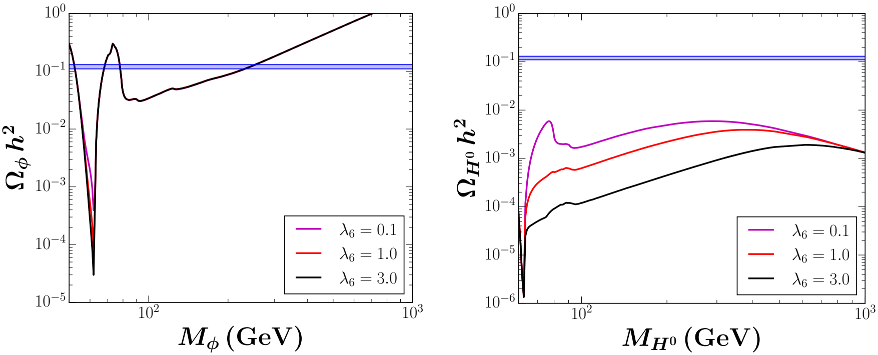
$$\frac{dn_H}{dt} = -\sigma_v^{2200}\left(n_H^2 - \bar{n}_H^2\right) - \sigma_v^{2211}\left(n_H^2 - n_\phi^2\frac{\bar{n}_H^2}{\bar{n}_\phi^2}\right) - \frac{1}{2}\sigma_v^{1210}n_\phi\left(n_H - \bar{n}_H\right) + \frac{1}{2}\sigma_v^{1120}(n_\phi^2 - n_H\frac{\bar{n}_\phi^2}{\bar{n}_H}) - 3\mathcal{H}n_H.$$

$$\bar{n}_a\bar{n}_b\sigma_v^{abcd} = \bar{n}_c\bar{n}_d\sigma_v^{cdab},$$

Boltzmann eqs are solved via `micrOMEGAs 5.2.13`.

Parameter dependence: DM conversion

$\lambda_7 = 0,\ \lambda_{S1} = \lambda_L = 0.1, \quad M_{H^\pm}/M_{H^0} = 1.1,\ \frac{M_{H^0}}{M_\phi} = 1.2.$



- Quartic interaction λ_6 affects Ω_{H^0}; the effect on Ω_ϕ is negligible.
- Ω_ϕ is determined by the Higgs-mediated interactions of the singlet scalar model. Therefore the same stringent DD constraints apply.

Parameter dependence: DM conversion

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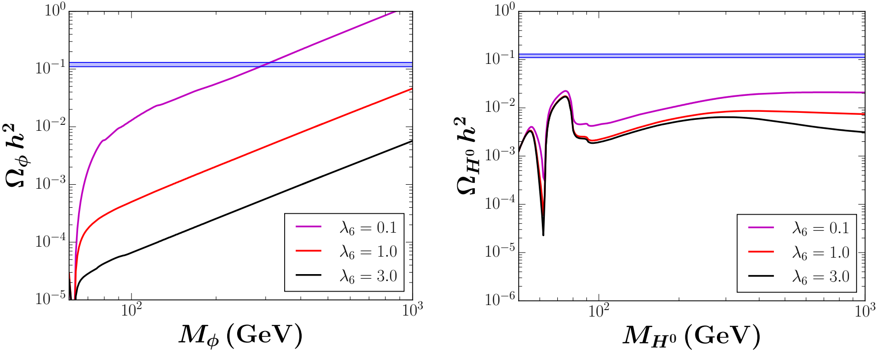
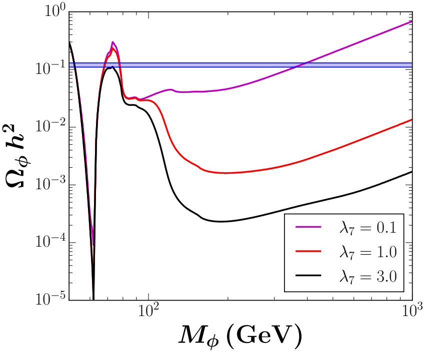
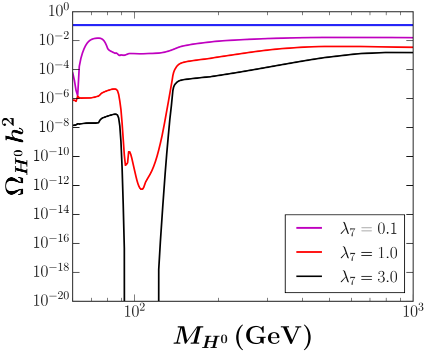


- λ_6 deeply affects Ω_ϕ; the effect on Ω_{H^0} is slightly small.
- Ω_{H^0} is determined by the Higgs portal interactions. Stringent DD constraints apply.

Parameter dependence: DM semiannihilation

$\lambda_6 = 0,\ \lambda_{S1} = \lambda_L = 0.1, \quad M_{H^\pm}/M_{H^0} = 1.1,\ \frac{M_{H0}}{M_\phi} = 1.2.$

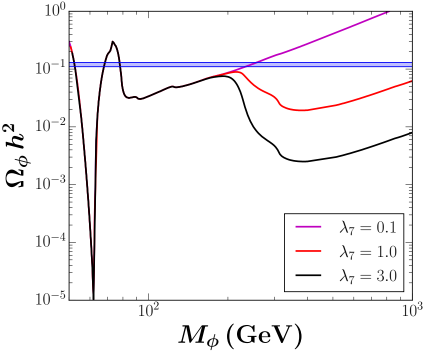


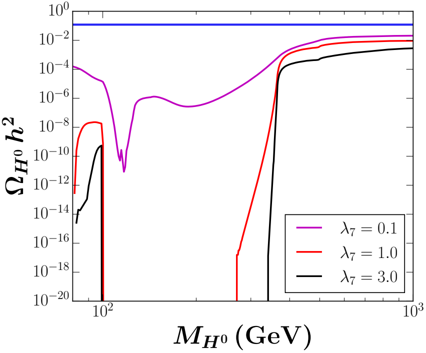


- Ω_{H^0} can be suppressed by orders of magnitude as a consequence of the exponential suppression $\phi + H^{0\dagger} \leftrightarrow \phi^\dagger + h$: $dY_{H^0}/dT \propto \sigma_v^{1210} Y_\phi Y_{H^0}$.
- Ω_{H^0} increases rapidly once the process $\phi + \phi \to H^0 + h$ is open.
- At intermediate values of M_ϕ, Ω_ϕ can be reduced by up to two orders of magnitude.

Parameter dependence: DM semiannihilation

$$\lambda_6 = 0,\ \lambda_{S1} = \lambda_L = 0.1, \quad M_{H^\pm}/M_{H^0} = 1.1,\ \frac{M_{H0}}{M_\phi} = 1.6.$$





Parameter dependence: DM semiannihilation

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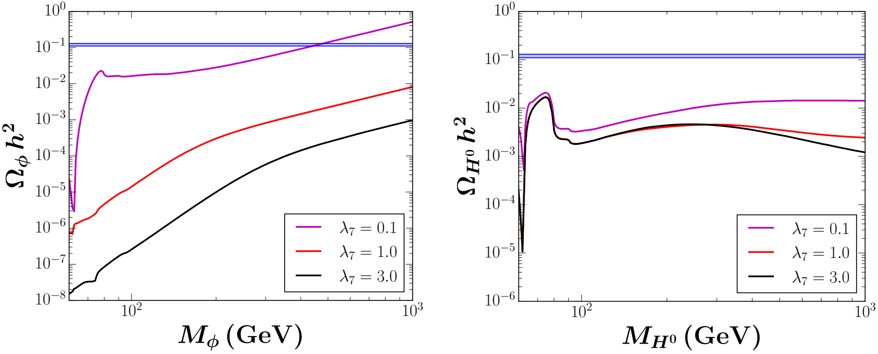

- λ_7 leads to a large reduction of Ω_ϕ while Ω_{H^0} is slightly affected.
- At intermediate values of M_{H^0}, Ω_{H^0} can be reduced by one order of magnitude.

Parameter dependence: DM semiannihilation

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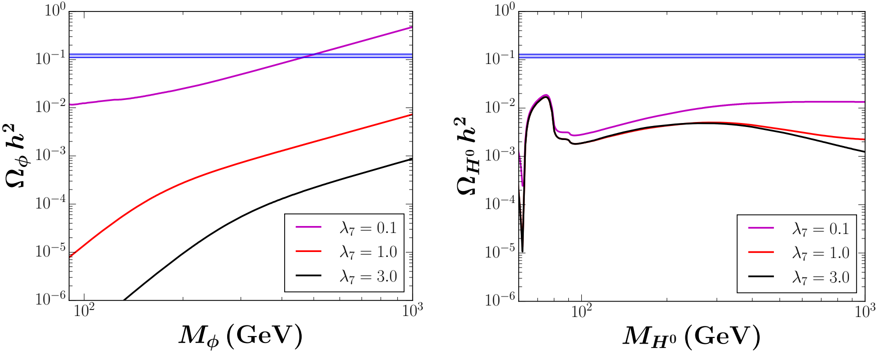

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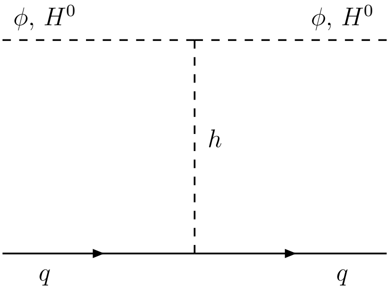
Direct detection

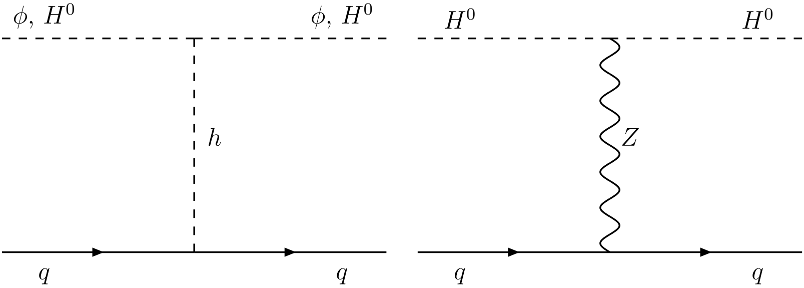


$$\sigma_N^{\rm SI} = \frac{\mu_N^2}{\pi}\frac{[Z(f_p^S + f_p^V) + (A-Z)(f_n^S + f_n^V)]^2}{A^2},$$

$$f_N^S = -\lambda_{Si}\frac{m_N f_N}{m_h^2 M_{\phi_i}}, \qquad f_{p,n} \approx 0.3,$$

$$f_p^V = f_n^V = 0.$$

Direct detection



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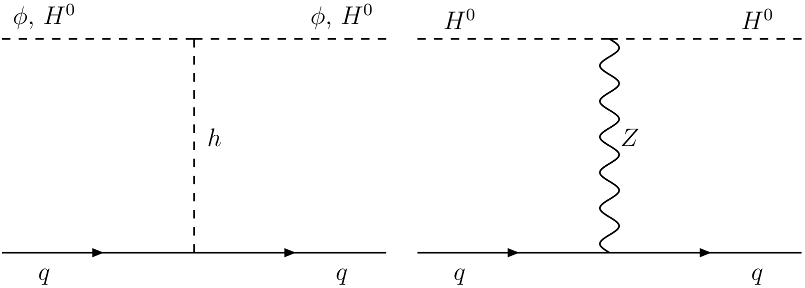
$$f_p^V = -(1 - 4 s_W^2) \frac{G_F}{\sqrt{2}}, \qquad f_n^V = \frac{G_F}{\sqrt{2}}.$$

Direct detection



$$\sigma_N^{\rm SI} = \frac{\mu_N^2}{\pi}\frac{\left[Z(f_p^S+f_p^V)+(A-Z)(f_n^S+f_n^V)\right]^2}{A^2},$$

For $|\lambda_L| < 3$ and $M_{H^0} \gtrsim 100$ GeV the cross section becomes

$$\sigma_{H^0} \approx \frac{G_F^2}{2\pi}\frac{\mu_N^2}{A^2}\left[(A-Z) - Z(1-4s_W^2)\right]^2 = 2\times 10^{-3}\,\text{pb}. \qquad (1)$$

Thus, in order to be below the upper bound imposed by Xenon1T the relic density must be suppressed at least by 6 orders of magnitude.

Constraints

Scalar potential: bounded from below

$$\lambda_{1,2} > 0, \;\; \lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1 \lambda_2} > 0, \;\; \lambda_3 + 2\sqrt{\lambda_1 \lambda_2} > 0.$$

Contribution to the oblique parameters S, T:

$$S = -\frac{\ln(r)}{6\pi}; \qquad r = M_{H^\pm}/M_{H^0},$$
$$T = \frac{M_{H^0}^2}{16\pi m_W^2 s_W^2} \frac{r^4 - 1 - 4r^2 \ln r}{r^2 - 1}.$$

LEP the constraints:

$$M_{H^0} + M_{H^\pm} > M_W, \;\; 2M_{H^0} > M_Z, \;\; 2M_{H^\pm} > M_Z, \;\; M_{H^\pm} > 70\,\mathrm{GeV}.$$

Constraints

Invisible Higgs decays: $\mathcal{B}_{inv} \leq 0.13$.

$$\Gamma(h \to \phi_i^* \phi_i) = \frac{\lambda_{Si}^2 v^2}{16\pi M_h} \left[1 - \frac{4M_{\phi_i}^2}{M_h^2}\right]^{1/2} ,$$

Higgs diphoton decay:

$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{\mathrm{Z_N}}}{\sigma(pp \to h \to \gamma\gamma)^{\mathrm{SM}}} = \frac{\sigma(pp \to h \to \gamma\gamma)^{\mathrm{IDM}}}{\sigma(pp \to h \to \gamma\gamma)^{\mathrm{SM}}} \approx \frac{\left[\mathrm{Br}(h \to \gamma\gamma)\right]^{\mathrm{IDM}}}{\left[\mathrm{Br}(h \to \gamma\gamma)\right]^{\mathrm{SM}}} .$$

$$R_{\gamma\gamma}^{\mathrm{ATLAS}} = 1.03^{+0.12}_{-0.12} , \qquad R_{\gamma\gamma}^{\mathrm{CMS}} = 1.12^{+0.09}_{-0.09} .$$

$$R_{\gamma\gamma} = \left| 1 + \frac{1}{A_{SM}} \left[\frac{\lambda_3 v^2 \, A_S(\tau_{H^\pm})}{2M_{H^\pm}^2}\right]\right|^2 ,$$

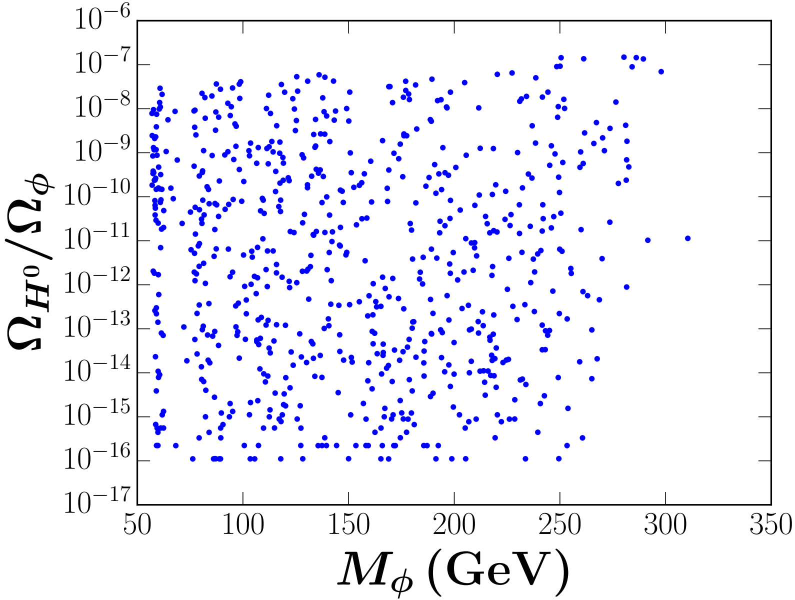
$A_{\mathrm{SM}} = -6.5$, $A_S(\tau) = -\tau^{-2}(\tau - \arcsin^2\sqrt{\tau})$, $\tau_{H^\pm} = M_h^2/(4M_{H^\pm}^2)$.

Viable parameter space

$$40\,\text{GeV} \leq M_\phi, M_{H^0} \leq 1\,\text{TeV},$$
$$1 < M_{H^0}/M_\phi < 2,$$
$$1 < M_{H^0}/M_{H^\pm} < 3,$$
$$10^{-4} \leq |\lambda_{S1}|, |\lambda_L|, |\lambda_6|, |\lambda_7| \leq 3,$$

$$\Omega_\phi + \Omega_{H^0} = \Omega_{\text{DM}}. \qquad \Omega_{\text{DM}} h^2 = 0.12 \pm 0.01.$$

Relic density



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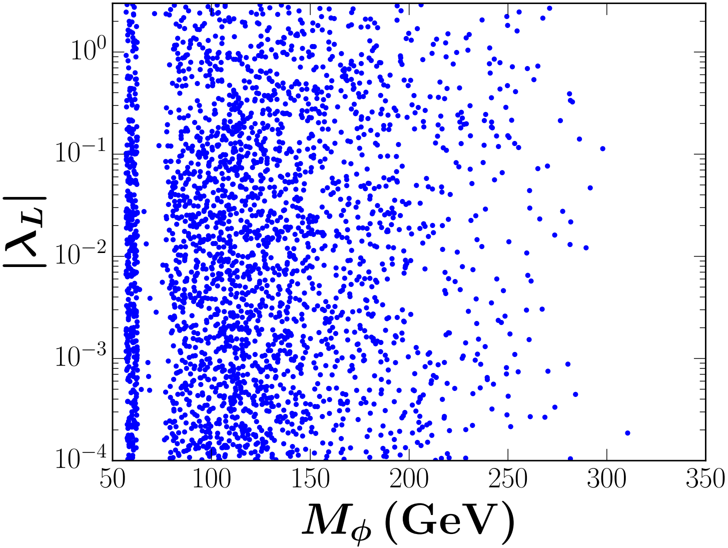

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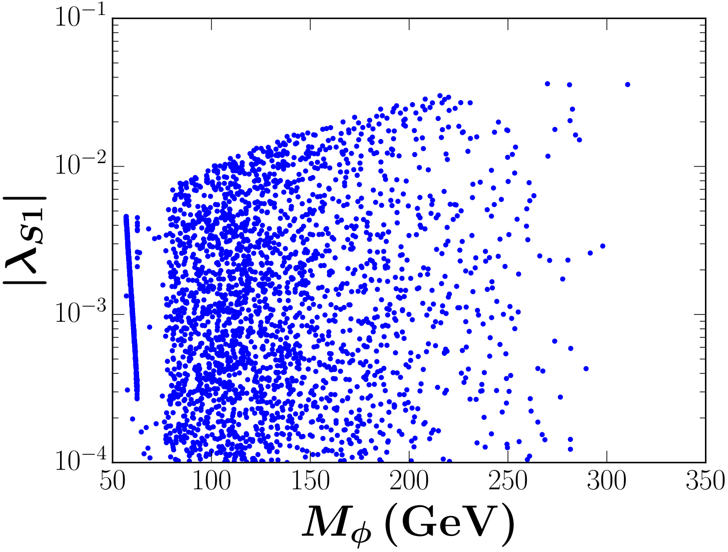

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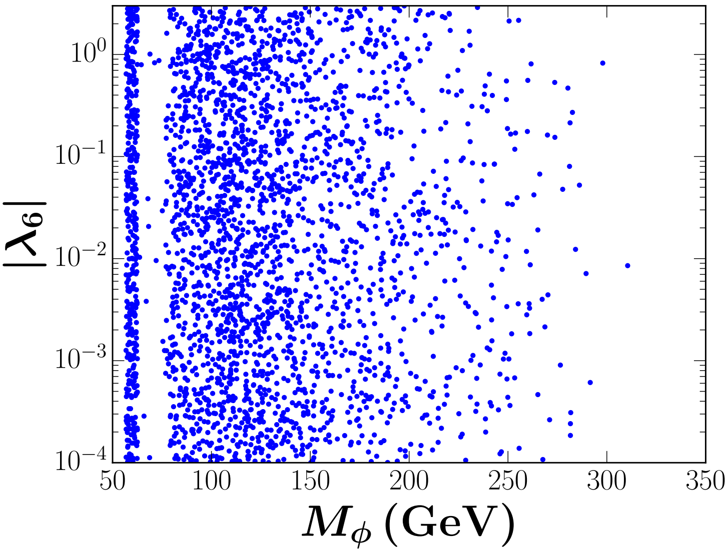

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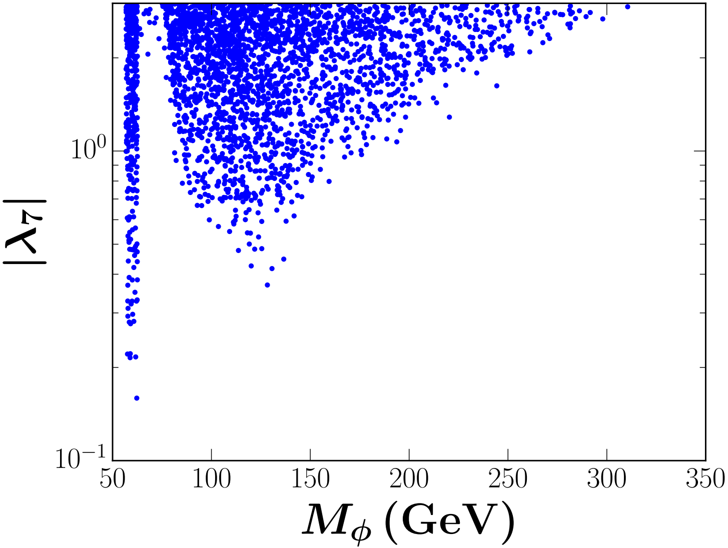

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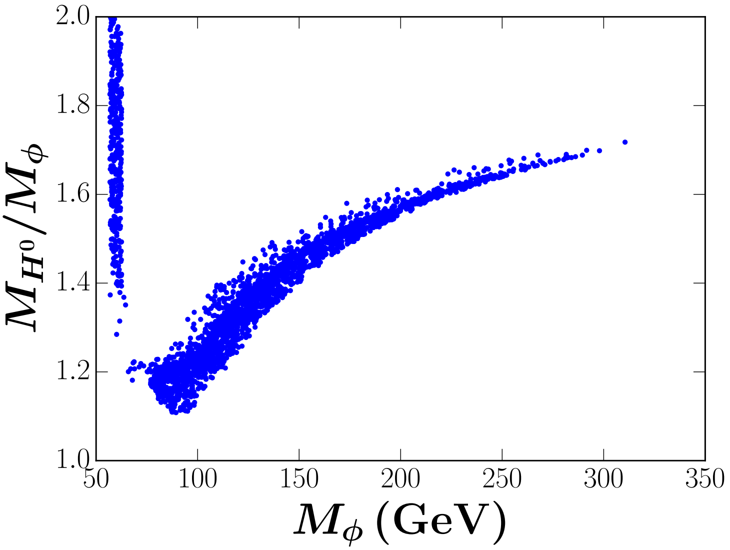

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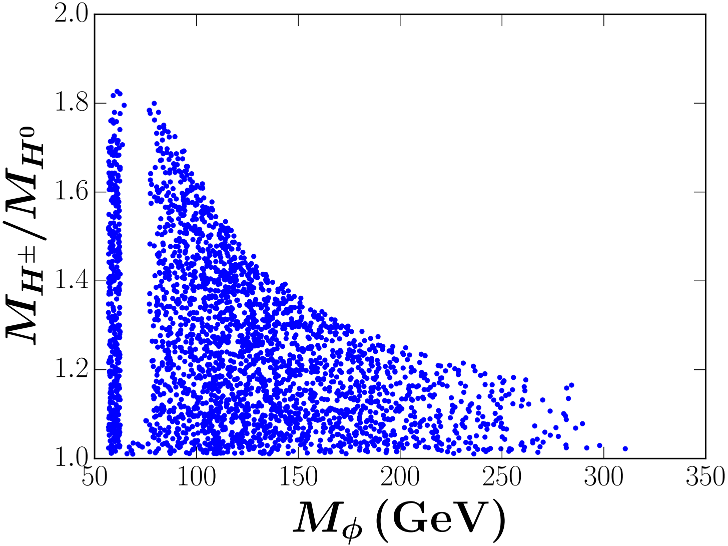
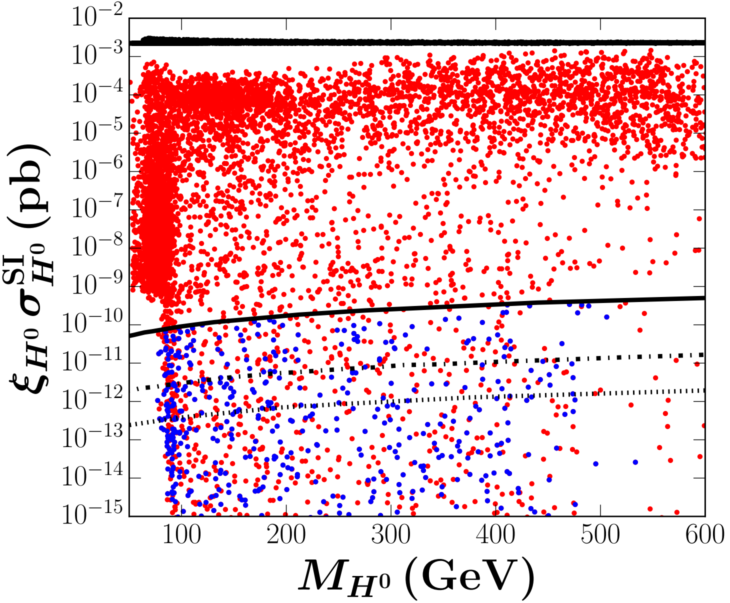
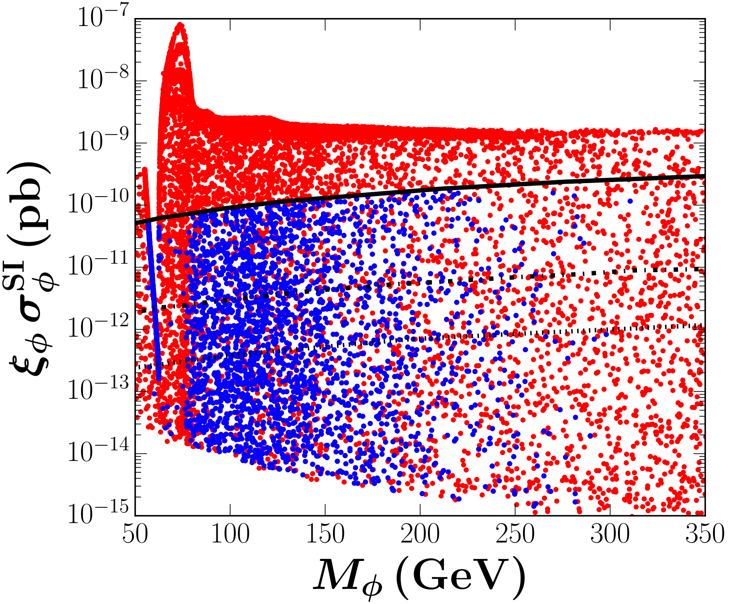


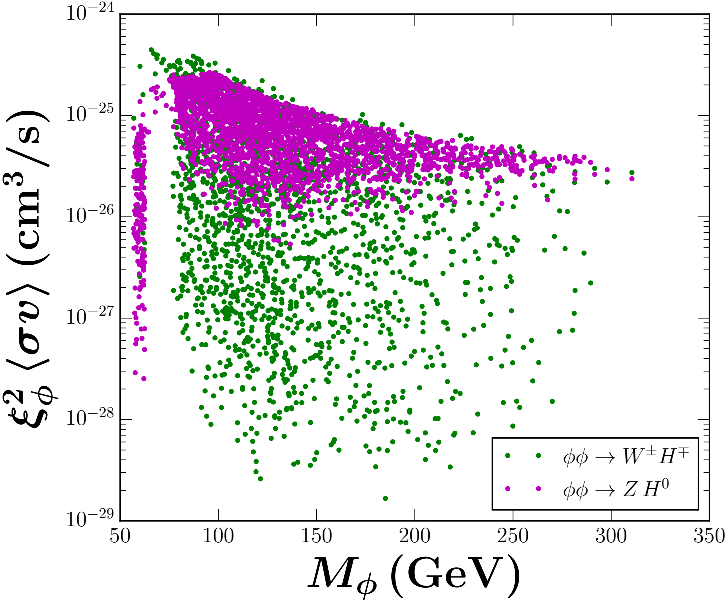
Direct detection: H^0



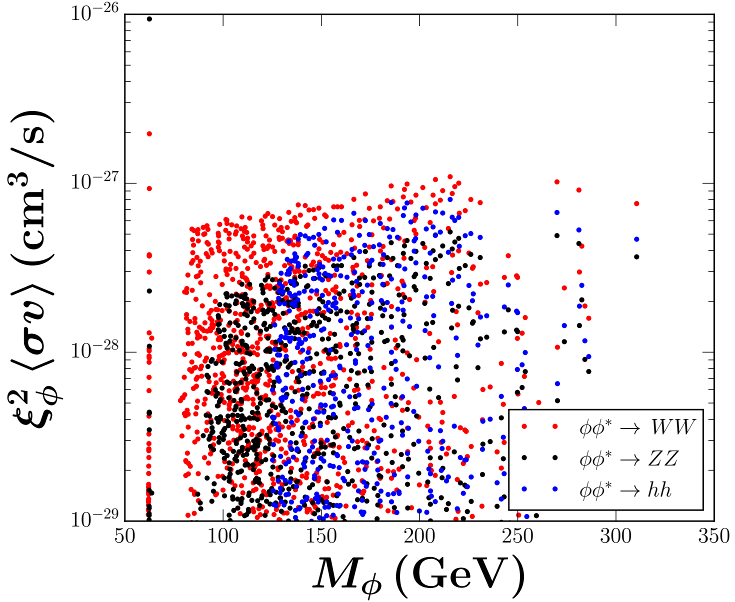
Direct detection: ϕ



Indirect detection: ϕ



Indirect detection: ϕ



Summary

1. The interplay of the SS and IDM models allows us to have a viable multicomponent scalar complex scenario compatible with all DM constraints.
2. Due to semiannihilations it is possible to satisfy $\Omega \approx 0.25$ and current DD limits over the mass range $M_\phi = (50, 350)$ GeV (by reducing couplings of each DM component to the Higgs).
3. Ω_{DM} is always dominated by the lighter DM particle ϕ.
4. DD experiments offer great prospects to test this model, including the possibility of observing signals from *both* DM particles.
5. The most promising process for ID is $\phi + \phi \to W^\pm + H^\mp, Z + H^o$.

Besides being simple and well-motivated, Z_N models are consistent and testable frameworks for two-component dark matter.