Multi-component dark matter*

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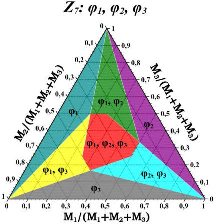


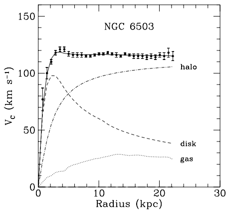
XIV SILAFAE - Ecuador, 14.11.2022

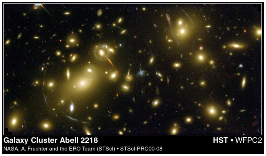
* In coll. with C. Yaguna, JHEP21,PRD22

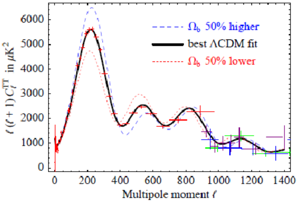
Outline

* Implications of direct searches on simplified WIMP models
* Z_N two-component scalar DM
* Z_4 two-component fermion-scalar model
* Conclusions

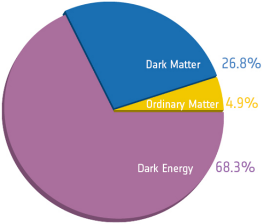
Evidence for dark matter is abundant and compelling







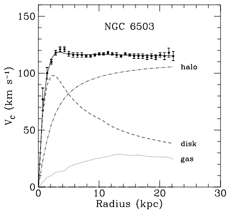
- Galactic rotation curves
- Cluster and supernova data
- Bullet cluster
- Weak lensing
- CMB anisotropies
- Big bang nucleosynthesis



DM: massive, neutral, stable.

Despite of this evidence the nature of DM is still unknown.

Evidence for dark matter is abundant and compelling



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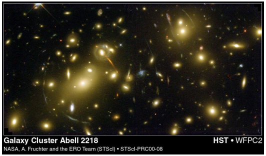
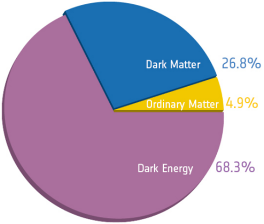
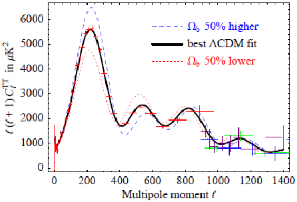






DM: massive, neutral, stable.

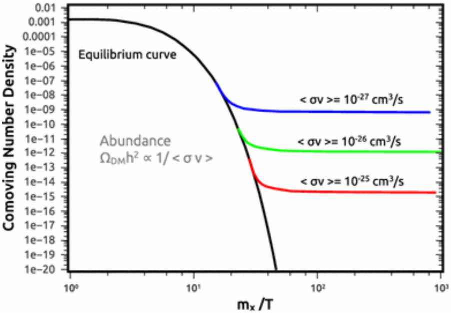
Despite of this evidence the nature of DM is still unknown.

WIMP paradigm

• WIMPs are among the most well-motivated candidates since the thermal annihilation cross section needed to account for the observed DM relic density is obtained for DM particles with electroweak interactions and masses.

• Their abundance is governed by the generic mechanism of chemical frezee-out which has also played a role in the abundance of light elements as well as the CMB radiation, both in stark agreement with current observations.

• WIMPs may be explored through direct, indirect and collider searches.



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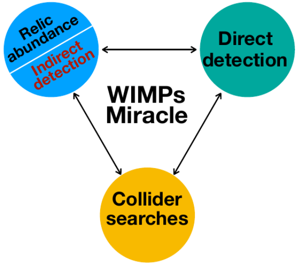

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Single WIMP scenarios

It is usually assumed that:

• DM is explained by a single candidate: scalar, fermion o vector.

• A *discrete* symmetry forbids the DM decay: $Z_2, Z_3, ...$

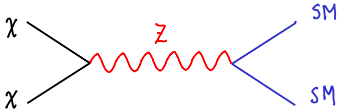
• For a extended dark sector, the lightest particle is the candidate.

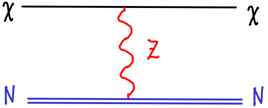
• Gauge-invariant renormalizable portals are possible for scalar DM: Higgs portal ($S^\dagger S H^\dagger H$) and Z portal $(D_\mu S)^\dagger(D^\mu S)$.

• If it is a fermion singlet, either a nonrenormalizable operator or a new messenger that mixes with the SM Higgs must be invoked.

Simplified models with a unique SM portal

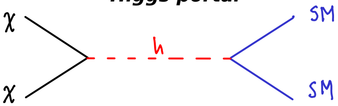
Z portal

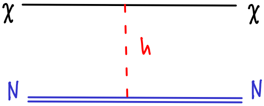




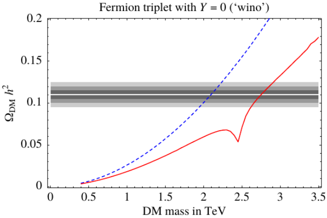
$\sigma_{\chi N} \sim 10^{-39}\,\mathrm{cm}^2$

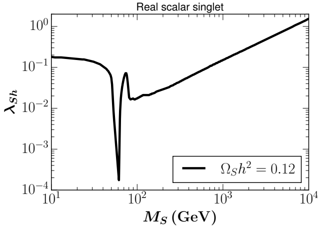
Higgs portal



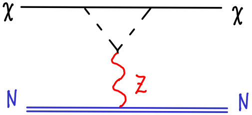


$\sigma_{\chi N} \sim [10^{-47}, 10^{-44}]\ \mathrm{cm}^2$





- Loop suppressed: $\sigma_{\chi N} \lesssim 10^{-46}\ \mathrm{cm}^2$



DD implications on WIMP models

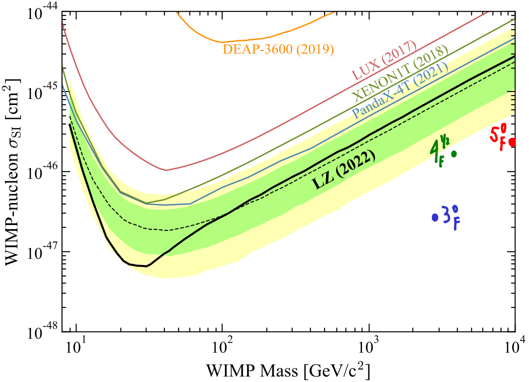
It is not free of challenges, both at th. and exp. levels

⋆ May need some degree of fine tuning.

⋆ The null results have lead to more and more constraints.

• DD limits have already excluded simplified models with a gauge portal.
These exclude any $SU(2)_L$ multiplet with $Y \neq 0$: $\sigma_{\chi N} \sim 10^{-39}\,\mathrm{cm}^2$.

• A sufficient mass spitting between the neutral components can help to alleviate such constraints: e.g. quadruplet.

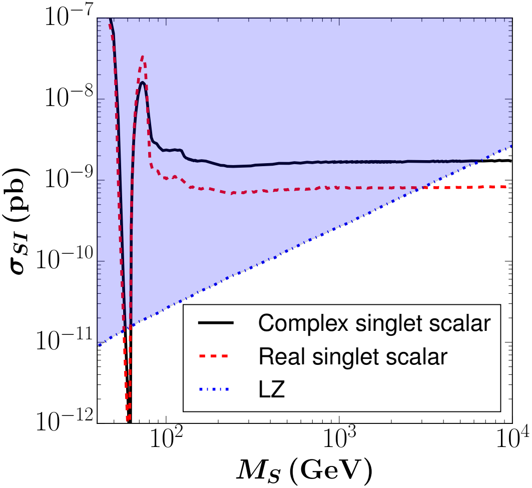


DD implications on WIMP models

- Higgs portal models: DD substantially constrains the DM mass region to lie around the Higgs resonance or above the TeV scale.

$\mathcal{V} \supset \frac{1}{2} M_S S^2 + \lambda_{Sh} S^2 H^\dagger H.$

LZ $\Rightarrow$ $M_S \gtrsim 3\,(6)$ TeV,
$\lambda_{Sh} \gtrsim 0.4\,(3)$.



We are at a crucial moment in the construction of WIMP DM models where it is being reassessed that the SM portal is the dominant one.

Multicomponent DM

- It may be that the DM is actually composed of several species (as the visible sector): $\Omega_{DM} = \Omega_{\chi 1} + \Omega_{\chi 2} + ...$

QUARKS

The u-, d-, and s-quark masses are the $\overline{\text{MS}}$ masses at the scale μ = 2 GeV. The c- and b-quark masses are the $\overline{\text{MS}}$ masses renormalized at the $\overline{\text{MS}}$ mass, i.e. $\overline{m} = \overline{m}(\mu = \overline{m})$. The t-quark mass is extracted from event kinematics (see the review "The Top Quark").

u $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_u = 2.16^{+0.49}_{-0.26}$ MeV $\quad$ Charge $= \frac{2}{3}\,e$ $\quad I_z = +\frac{1}{2}$
$m_u/m_d = 0.474^{+0.056}_{-0.074}$

d $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_d = 4.67^{+0.48}_{-0.17}$ MeV $\quad$ Charge $= -\frac{1}{3}\,e$ $\quad I_z = -\frac{1}{2}$
$m_s/m_d = 17$–22
$\overline{m} = (m_u + m_d)/2 = 3.45^{+0.35}_{-0.15}$ MeV

s $\quad I(J^P) = 0(\frac{1}{2}^+)$

$m_s = 93.4^{+8.6}_{-3.4}$ MeV $\quad$ Charge $= -\frac{1}{3}\,e$ $\quad$ Strangeness $= -1$
$m_s\ /\ ((m_u + m_d)/2) = 27.33^{+0.67}_{-0.77}$

c $\quad I(J^P) = 0(\frac{1}{2}^+)$

$m_c = 1.27 \pm 0.02$ GeV $\quad$ Charge $= \frac{2}{3}\,e$ $\quad$ Charm $= +1$
$m_c/m_s = 11.76^{+0.05}_{-0.10}$
$m_b/m_c = 4.58 \pm 0.01$
$m_b - m_c = 3.45 \pm 0.05$ GeV

b $\quad I(J^P) = 0(\frac{1}{2}^+)$

$m_b = 4.18^{+0.03}_{-0.02}$ GeV $\quad$ Charge $= -\frac{1}{3}\,e$ $\quad$ Bottom $= -1$

WIMP and Dark Matter Searches

No confirmed evidence found for galactic WIMPs from the GeV to the TeV mass scales and down to 1×10^{-10} pb spin independent cross section at M = 100 GeV.

χ1 $\quad I\,(J^P) = ?\,(?^?)$

$m_{\chi 1} = ?$, $\quad$ Charge 0, $\; I_z = ?$.

χ2 $\quad I\,(J^P) = ?\,(?^?)$

$m_{\chi 2} = ?$, $\quad$ Charge 0, $\; I_z = ?$.

χ3 $\quad I\,(J^P) = ?\,(?^?)$

$m_{\chi 3} = ?$, $\quad$ Charge 0, $\; I_z = ?$.

χ4 $\quad I\,(J^P) = ?\,(?^?)$

$m_{\chi 4} = ?$, $\quad$ Charge 0, $\; I_z = ?$.

χ5 $\quad I\,(J^P) = ?\,(?^?)$

$m_{\chi 5} = ?$, $\quad$ Charge 0, $\; I_z = ?$.

Multicomponent DM

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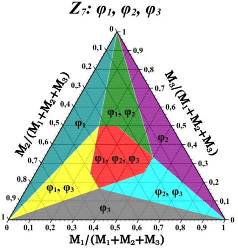

• These scenarios not only are perfectly consistent with observations but often lead to testable predictions in current and future DM exps.

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

Several Z_2's might be used (e.g. $Z_2 \otimes Z_2'$) but these constructions do not bring new DM processes and Ω_{DM} is likely to be determined by the Higgs portal interactions, hence the same stringent DD constraints apply.

Z_N multicomponent scalar scenarios

Multi-component DM models featuring scalar fields that are simultaneously stabilized by a single Z_N symmetry.

- For k DM particles, they require k complex scalar fields that are SM singlets but have different charges under a Z_N ($N \geq 2k$).
- DM stability depends on the masses.
- New DM processes contributing to $\langle \sigma v \rangle$.
- These Z_N scenarios are realizations of the Higgs portal.
- It could be a remnant of a spontaneously broken $U(1)$ gauge symmetry and thus be related to gauge extensions of the SM.

Z_4 two-component scalar DM model

$N = 4$ involves one complex field and one real field

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Z_4 scalar model: interactions

$\phi_{1,2}$ singlets under $\mathcal{G}_{SM}$ whereas the SM particles are singlets under Z_4.

$$\phi_1 \sim \omega_4, \;\; \phi_2 \sim \omega_4^2; \qquad \omega_4 = \exp(i2\pi/4).$$

$$\mathcal{V} \supset \lambda_{412}|\phi_1|^2\phi_2^2 + \lambda_{S1}|H|^2|\phi_1|^2 + \frac{1}{2}\lambda_{S2}|H|^2\phi_2^2 + \frac{1}{2}\left[\mu_{S1}\phi_1^2\phi_2 + \text{h.c.}\right].$$

$\langle\phi_{1,2}\rangle = 0$ and $M_2 < 2M_1$ so that ϕ_2 remains stable.

Set of free parameters:

$$M_1, M_2, \lambda_{S1}, \lambda_{S2}, \lambda_{412}, \mu_{S1}.$$

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
$\phi_1 + \phi_1^\dagger \to \phi_2 + \phi_2$	1122
$\phi_1 + \phi_1 \to \phi_2 + h$	1120

ϕ_2 Processes	Type
$\phi_2 + \phi_2 \to SM + SM$	2200
$\phi_2 + \phi_2 \to \phi_1 + \phi_1^\dagger$	2211
$\phi_2 + \phi_1 \to \phi_1^\dagger + h$	2110
$\phi_2 + h \to \phi_1 + \phi_1$	2011

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`.

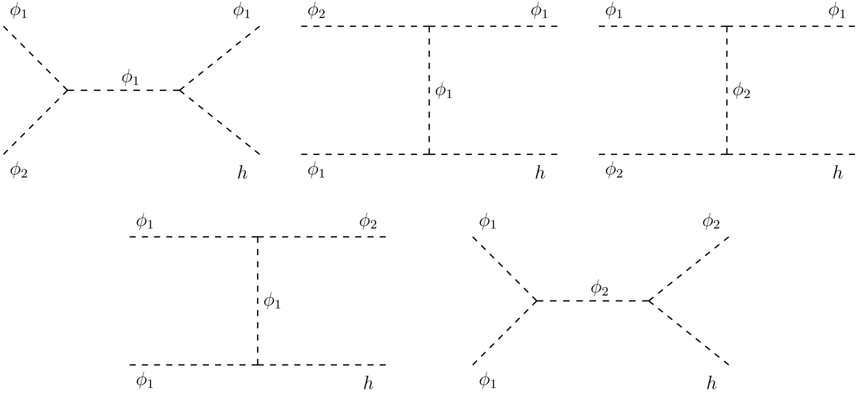
$$\frac{dn_1}{dt} = -\sigma_v^{1100}\left(n_1^2 - \bar{n}_1^2\right) - \sigma_v^{1120}\left(n_1^2 - n_2\frac{\bar{n}_1^2}{\bar{n}_2}\right) - \sigma_v^{1122}\left(n_1^2 - n_2^2\frac{\bar{n}_1^2}{\bar{n}_2^2}\right) - 3Hn_1,$$

$$\frac{dn_2}{dt} = -\sigma_v^{2200}\left(n_2^2 - \bar{n}_2^2\right) - \sigma_v^{2211}\left(n_2^2 - n_1^2\frac{\bar{n}_2^2}{\bar{n}_1^2}\right) - \frac{1}{2}\sigma_v^{1210}\left(n_1 n_2 - n_1\bar{n}_2\right)$$
$$+ \frac{1}{2}\sigma_v^{1120}(n_1^2 - n_2\frac{\bar{n}_1^2}{\bar{n}_2}) - 3Hn_2.$$

DM semiannihilations

Semi-annihilation processes involve $\mu_{S1}\lambda_{Si}$.

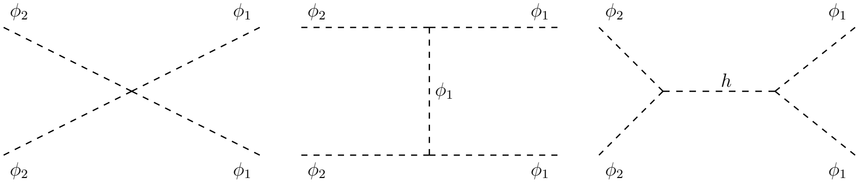
$$\phi_2 + \phi_1 \to \phi_1^\dagger + h, \qquad \phi_1 + \phi_1 \to \phi_2 + h$$



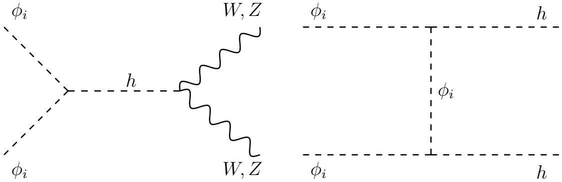
Processes in the top panels modify n_2 by one unit whereas those in the bottom panels change n_1 by two units and n_2 by one unit.

DM conversion processes

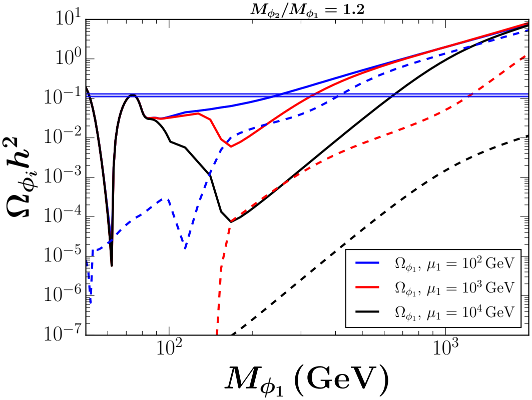
Conversion via λ_{412}, μ_{S1}^2, or $\lambda_{S1}\lambda_{S2}$.



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

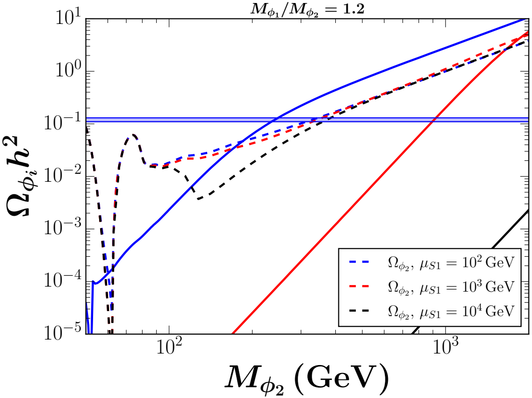


Parameter dependence: $M_{\phi_1} < M_{\phi_2}$



- Ω_2 can be suppressed by orders of magnitude as a consequence of the exponential suppression $\phi_1 + \phi_2 \leftrightarrow \phi_1 + h$: $dY_2/dT \propto \sigma_v^{1210} Y_1 Y_2$.
- Ω_2 increases rapidly once the process $\phi_1 + \phi_1 \to \phi_2 + h$ is kin. open.
- At intermediate values of M_{ϕ_1}, Ω_1 can be reduced by $\mathcal{O}(10^3)$.

Parameter dependence: $M_{\phi_2} < M_{\phi_1}$



- Semiannihilations can affect Ω_{ϕ_1} at low and intermediate masses.
- $\phi_1 + \phi_2 \to \phi_1 + h$ may reduce Ω_{ϕ_2} after ϕ_1 freeze-out is but it has a negligible effect on Ω_{ϕ_2} due to the small value of Ω_{ϕ_1}.

Viable parameter space

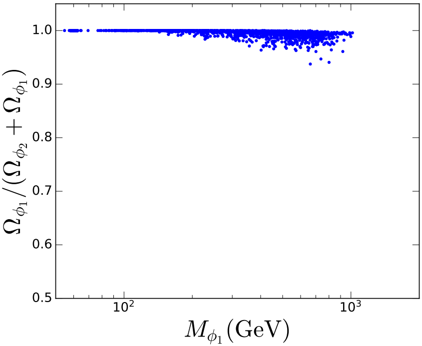
$$40\,\text{GeV} \leq M_{\phi_1,\phi_2} \leq 2\,\text{TeV},$$
$$10^{-4} \leq |\lambda_{Si}|, |\lambda_{412}| \leq 1,$$
$$100\,\text{GeV} \leq \mu_{S1} \leq 10\,\text{TeV}.$$

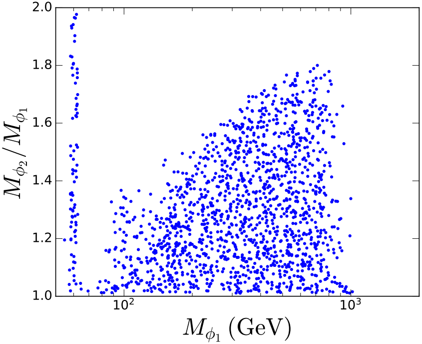
$$\Omega_{\phi_1} + \Omega_{\phi_2} = \Omega_{\text{DM}}. \qquad \Omega_{\text{DM}} h^2 = 0.12 \pm 0.01.$$

Excluded mass range in the singlet scalar Z_2 model:

- Real case: $M_W \lesssim M_S \lesssim 3$ TeV.
- Complex case: $M_W \lesssim M_S \lesssim 6$ TeV.

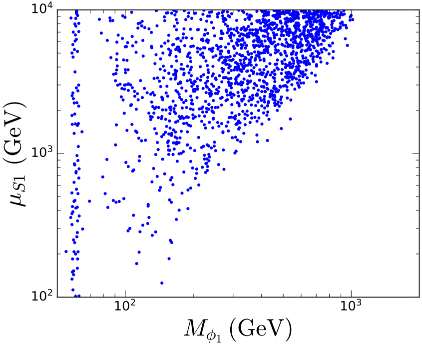
Z_4 model: $M_{\phi_1} < M_{\phi_2}$

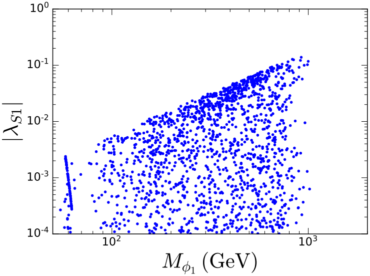


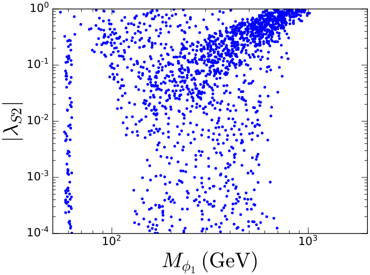


- ϕ_1 always gives the dominant contribution (more than 90% of Ω_{DM}).
- This hierarchy is a consequence of the new Z_4 interactions, which tend to suppress Ω of the heavier particle more than that of the lighter one.
- The masses are not required to be degenerate.

Z_4 scalar model: $M_{\phi_1} < M_{\phi_2}$

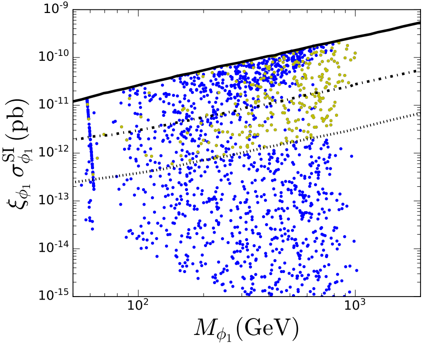


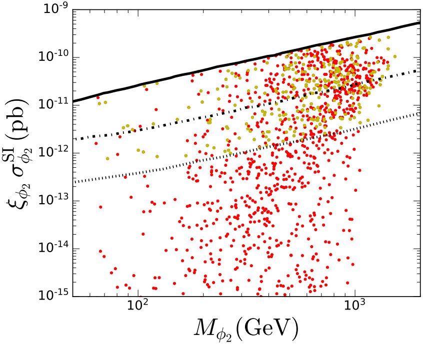




- The semiannihilation processes are essential to obtain the correct relic density while satifying DD bounds.
- The minimum value of μ_{S1} increases with M_{ϕ_1} up to about 1 TeV, when it reaches 10 TeV.
- At $M_{\phi_1} \approx 1$ TeV, λ_{S2} reaches the maximum value allowed in the scan.

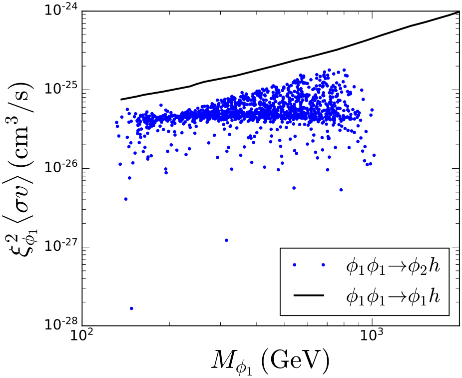
Direct detection: $M_{\phi_1} < M_{\phi_2}$





- 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.

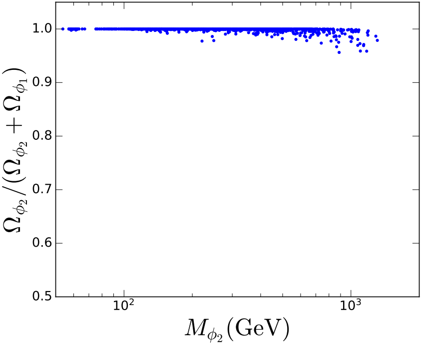
Indirect detection: $M_{\phi_1} < M_{\phi_2}$

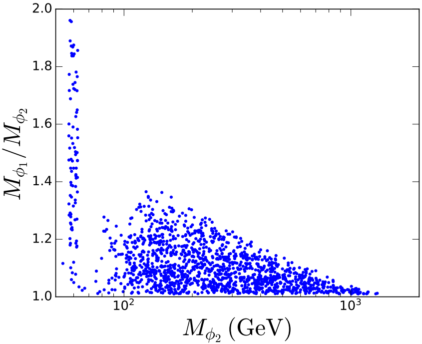


- $\phi_1\phi_1 \to \phi_2 h$ turns out to be the most relevant one $\sim 10^{-26}\mathrm{cm}^3/\mathrm{s}$.
- Due to the ξ_2 suppression and its higher mass, the ID signals involving ϕ_2 are less promising.

Z_4 model: $M_{\phi_2} < M_{\phi_1}$

The results are qualitatively similar to those for $M_{\phi_1} < M_{\phi_2}$. The main difference is that a mild degeneracy is required between $\phi_{1,2}$.

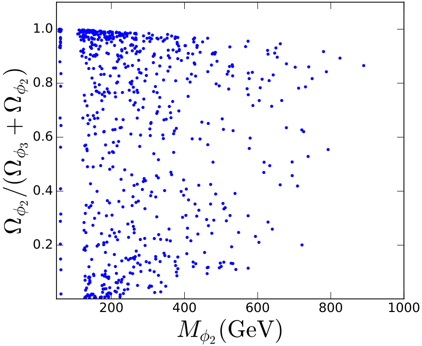


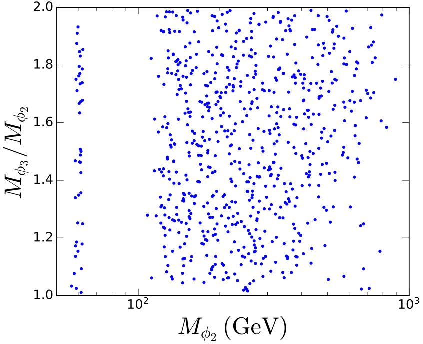


- ϕ_2 always gives the dominant contribution (more than 90% of Ω_{DM}).
- M_{ϕ_1}/M_{ϕ_2} does not exceed 1.4.

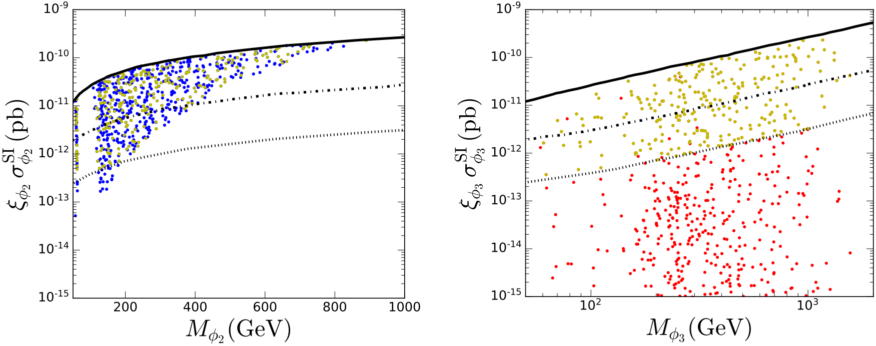
A Z_6 model

- $\phi_2 \sim \omega_6^2, \;\; \phi_3 \sim \omega_6^3.$ $\qquad \mathcal{V}_{Z_6}(\phi_2, \phi_3) \supset \frac{1}{3}\mu_{32}\phi_2^3 + \text{h.c.}.$
- ϕ_2 and ϕ_3 are both stable independently of their masses.





- Thanks to the semi-annihilation processes the mass range below 1 TeV turns out to be viable. $\phi_2 + \phi_2 \to \phi_2^* + h$.
- Both particles may contribute significantly.
- M_3/M_2 varies over a wide range: DM particles are not required to be degenerate.



- The detection of ϕ_2 at DARWIN is practically guaranteed for all the points in our sample.
- ID does not currently constraint this model.

Beyond two singlets: a singlet and a doublet under a Z_6

$H_2 \sim \omega_6^2, \;\; \phi \sim \omega_6^3 = -1.$

$$\mathcal{V}(\phi, H_2) \supset \lambda_{S1}|H_1|^2|\phi|^2 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2$$
$$+ \lambda_6|H_2|^2|\phi|^2 + \frac{1}{2}\left[\lambda_7\phi^2 H_2^\dagger H_1 + \text{h.c.}\right].$$

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

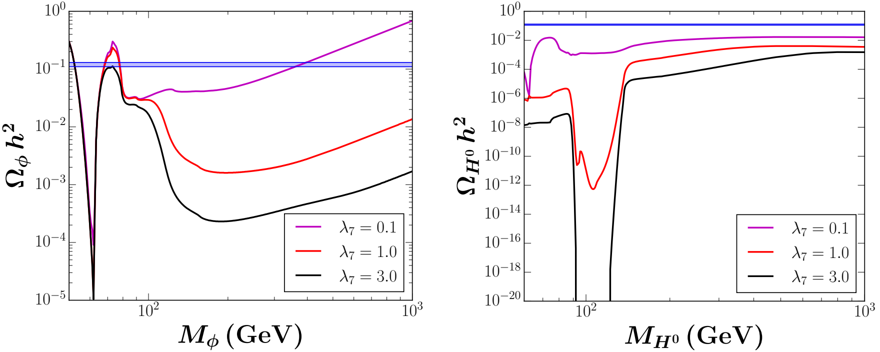
$$H_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}.$$

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

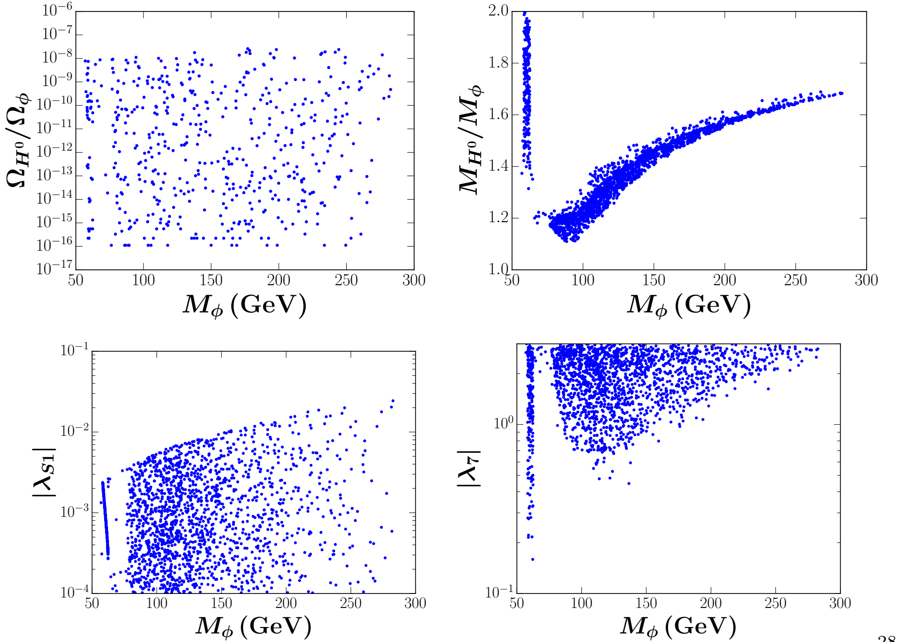
Parameter dependence: DM semiannihilation

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

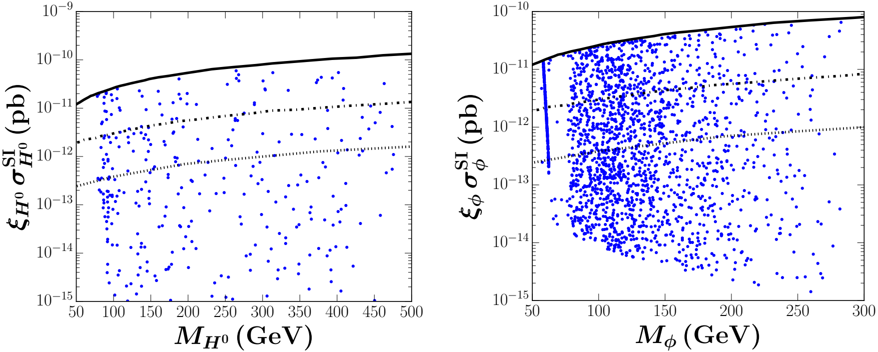


- Ω_{H^0} can be suppressed by orders of magnitude as a consequence of the exponential suppression $\phi + H^{0\dagger} \leftrightarrow \phi^\dagger + h$: $dY_{H^0}/dT \propto \sigma_v^{1210} Y_\phi Y_{H^0}$.
- Ω_{H^0} increases rapidly once the process $\phi + \phi \to H^0 + h$ is open.
- At intermediate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

Viable parameter space

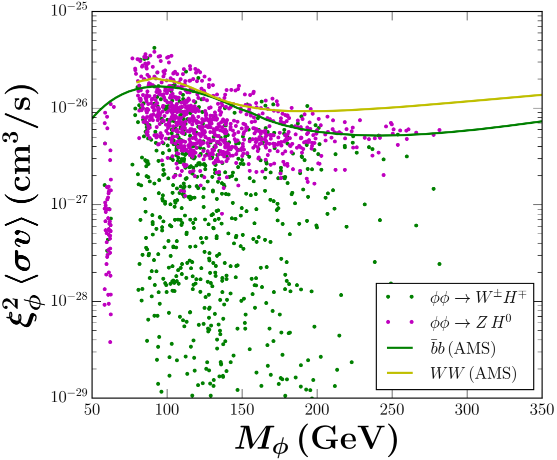


Direct detection



- Either DM particle may be observed in future DD experiments.
- Sizeable σ_{H_0} is compensated by a large suppression on Ω_{H_0}.

Indirect detection



- The most relelevant channel are $\phi + \phi \to W^{\pm} + H^{\mp}$, $Z + H^0$.
- AMS antiproton data is starting to probe this model.

Summary

In contrast with the singlet scalar model, it is indeed possible to satisfy current bounds with DM masses below the TeV scale.

1. The trilinear coupling, via the semi-annihilation processes it induces, plays an essential role in setting the DM abundances.
2. The lighter DM particle accounts for most of Ω_{DM}, except in the Z_6 model with two singlets.
3. DD experiments offer great prospects to test these model, including the possibility of observing signals from *both* dark matter particles. ID may play role for electroweak multiplets as DM candidates.
4. The results can be generalise to all the scenarios based on a Z_{2n} symmetry.

Fermion-scalar model: interactions

S, ψ singlets under $\mathcal{G}_{SM}$.

$$\psi_1 \sim \omega_4, \;\; S \sim \omega_4^2; \qquad \omega_4 = \exp(i2\pi/4).$$

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \lambda_S S^4 + \frac{1}{2}\lambda_{SH}|H|^2 S^2 + M_\psi \overline{\psi}\psi + \frac{1}{2} S[y_s \overline{\psi^c}\psi + y_p \overline{\psi^c}\gamma_5\psi + \text{h.c.}].$$

- $\langle S \rangle = 0$ and $M_S < 2M_\psi$ so that S remains stable.
- λ_{SH} plays a prominent role as it couples the DM sector with the SM.
- ψ interacts directly only with S.
- $\lambda_{SH} \neq 0$, but either y_s or y_p can in principle vanish.

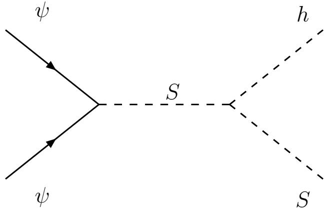
Set of free parameters: $M_S, M_\psi, \lambda_{SH}, y_s, y_p$.

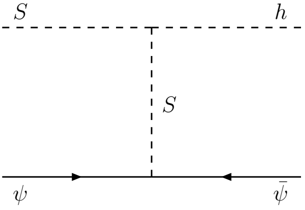
It is likely the simplest two-component DM model.

ψ Processes	Type
$\psi + \bar{\psi} \to S + S$	1122 C
$\psi + \psi \to S + h$	1120 SA

S Processes	Type
$S + S \to SM + SM$	2200 A
$S + S \to \psi + \bar{\psi}$	2211 C
$S + h \to \psi + \psi$	2011 SA
$S + \psi \to \bar{\psi} + h$	2110 SA

Semi-annihilation processes involve $y_{s,p}\lambda_{SH}$





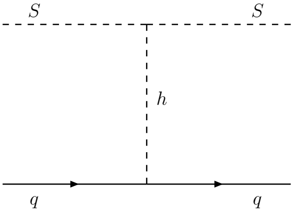
- $\psi\psi \to Sh$ becomes velocity suppressed for $y_p = 0$.
- $\psi S \to \bar{\psi}h$ does not suffer a velocity suppression in either case.
- When $M_\psi < M_S$, Ω_S can be an exponential suppressed by $Sh \to \psi\psi$.
- Ω_ψ tends to be larger than Ω_S.

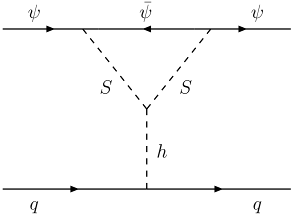
Viable parameter space

$$40\,\text{GeV} \leq M_\psi \leq 2\,\text{TeV}, \;\; M_S < 2M_\psi,$$
$$50\,\text{GeV} \leq M_S \leq 2\,\text{TeV}, \;\; M_S < 3M_\psi,$$
$$10^{-4} \leq |\lambda_{SH}| \leq 3, \qquad 10^{-2} \leq |y_s|, |y_p| \leq 3.$$

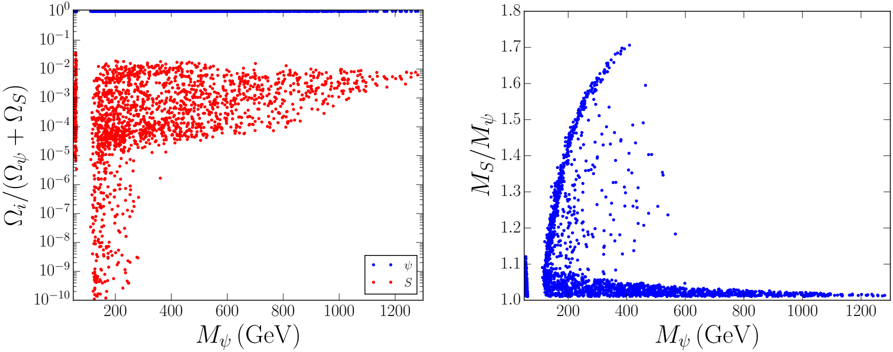
$$\Omega_S + \Omega_\psi = \Omega_{\text{DM}}. \qquad\qquad \Omega_{\text{DM}} h^2 = 0.12 \pm 0.01.$$

- At tree level, ψ cannot scatter elastically off nuclei.
- Even if loop-suppressed, this process will turn out to be within the sensitivity of current and future DD experiments, due to the significant values for y_s, y_p and λ_{SH} that are required to annihilate ψ.



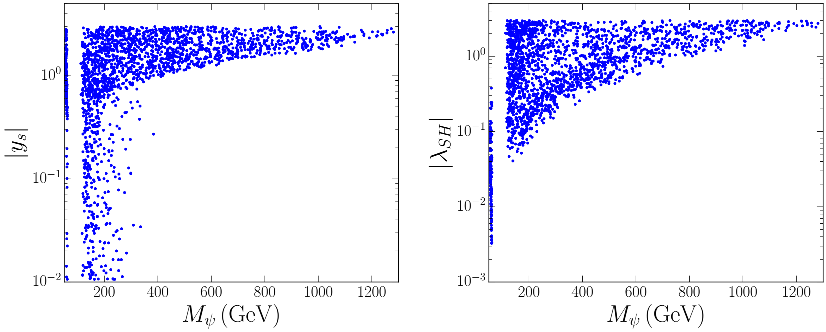


Viable paramenter space: $M_\psi < M_S$



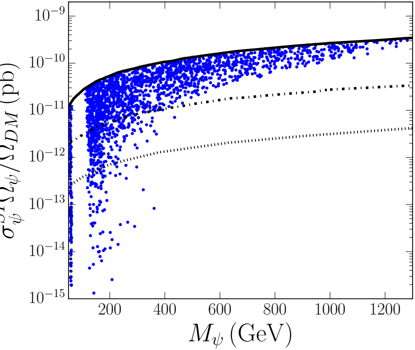
- S always contributes less than 10% of the DM density.
- Semiannihilations play a vital role: Ω_ψ can decrease significantly.
- M_S/M_ψ can reach sizable values (~ 1.7) up to $M_\psi \sim 600$ GeV.

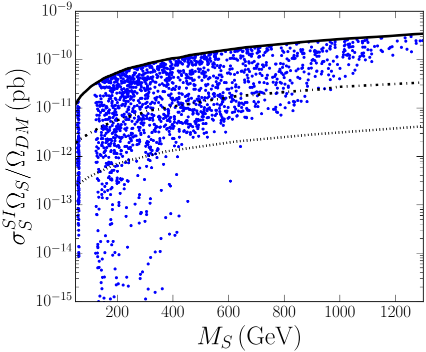
Viable paramenter space: $M_\psi < M_S$



• ϕ_1 Either y_s or y_p must be sizable ($\gtrsim 0.1$), along with λ_{SH}.
• The highest M_ψ corresponds to the region where λ_{SH} and y_s both reach the maximum value permitted by the scan.

Direct detection: $M_\psi < M_S$



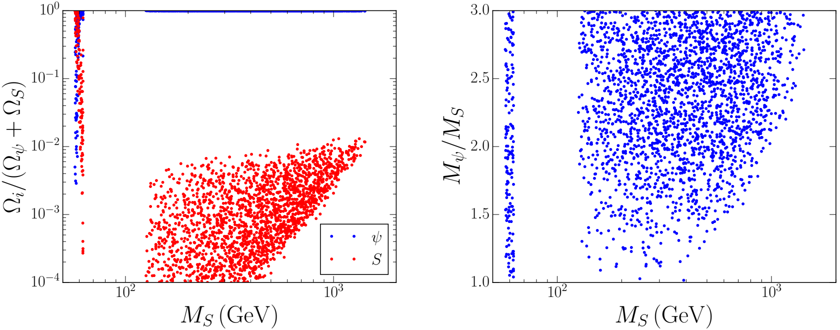


• Most models lie within the sensitivity of DARWIN and that a significant fraction of them lie just below the current limit.

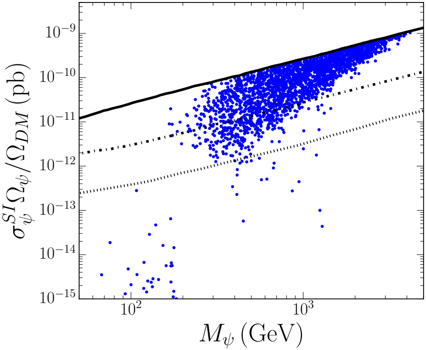
• This regime offers excellent prospects to be tested in current and planned DD experiments.

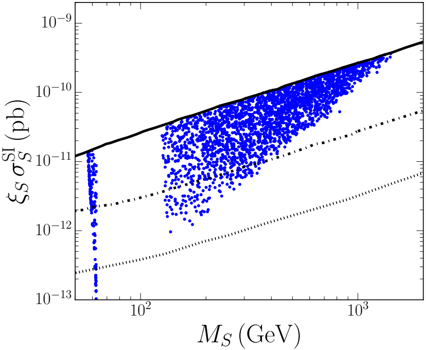
ID: The most promising process in both mass regimes is $\psi\psi \to Sh$. The viable models are below the limit (prospect) by FERMI (CTA).

Viable paramenter space: $M_S < M_\psi$



- ψ gives the dominant contribution for both mass regimes.
- M_ψ/M_S can take any value (unlike for the regime $M_\psi < M_S$) and Ω_S is not entirely driven by annihilations.





- Most points lie within the sensitivity of DARWIN.

- For the scalar there are practically no points that could escape future detection.

Summary

This model is a simple, predictive and testable scenario to explain DM.

1. DM masses below 1 TeV or so are allowed for both regimes.
2. The fermion gives the dominant contribution to the relic density.
3. The fermion DD cross section is detectable in spite of being generated at 1-loop.
4. This class of models can be considered as ultraviolet realizations of the fermionic Higgs portal.

$$\mathcal{O}_3 = (H^\dagger H)(\overline{\psi^c}\psi), \;\; \mathcal{O}_4 = (H^\dagger H)(\overline{\psi^c}\gamma_5\psi).$$

Concluding remarks

1. In the Z_N models it is possible to satisfy $\Omega \approx 0.25$ and current DD limits over the golden range of DM masses 100-1000 GeV.

2. In a sizable fraction of models both particles are predicted to be detectable, providing a way to differentiate these models from the usual scenarios with just one dark matter particle.

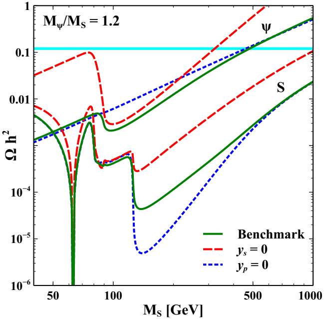
Besides being simple and well-motivated, these models are consistent and testable frameworks for two-component dark matter.

Starting point for futher implications such as neutrino masses, phase transitions, etc.

THANK YOU

Parameter dependence: $M_S < M_\psi$

benchmark model: $y_s = y_p = \lambda_{SH} = 1.$



Parameter dependence: $M_\psi < M_S$