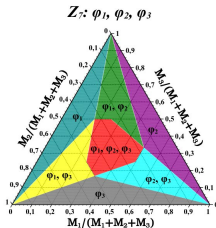


# Multi-component scalar dark matter: recent developments\*

Óscar Zapata

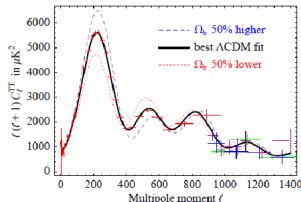
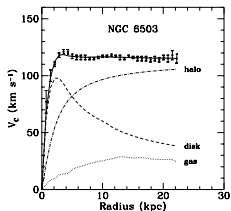
University of Antioquia (Colombia)



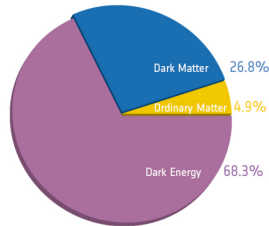
7th COMHEP - Villa de Leyva, 28.11.2022

\* In coll. with C. Yaguna; María José Rodríguez

# Evidence for dark matter is abundant and compelling



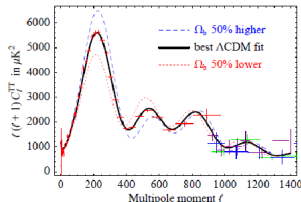
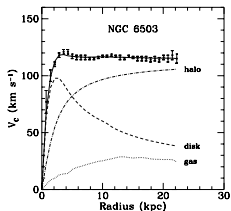
- Galactic rotation curves
- Cluster and supernova data
- Bullet cluster
- Weak lensing
- CMB anisotropies
- Big bang nucleosynthesis



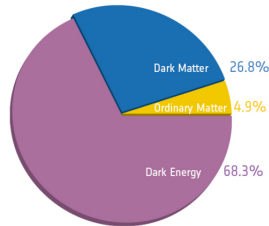
DM: massive, neutral, stable.

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

# Evidence for dark matter is abundant and compelling



- Galactic rotation curves
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DM: massive, neutral, stable.

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

# Single WIMP scenarios

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.

It is usually assumed that:

- DM is explained by a single candidate: scalar, fermion or vector.
- A *discrete* symmetry forbids the DM decay:  $Z_2, Z_3, \dots$
- For an 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  $(D_\mu S)^\dagger (D^\mu S)$ .

# DD implications on WIMP models

It is not free of challenges, both at theoretical and experimental

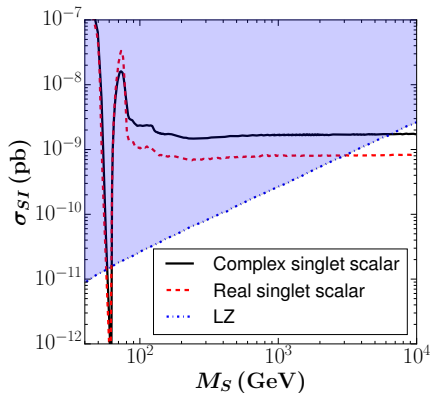
- ★ May need some degree of fine tuning.
- ★ The null results have lead to stringent constraints.

- Higgs portal models:

$M_{DM}$  lies around the Higgs resonance or above the TeV scale.

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

$$\text{LZ} \Rightarrow \begin{aligned} M_S &\gtrsim 3 \text{ (6) TeV,} \\ \lambda_{Sh} &\gtrsim 0.4 \text{ (3).} \end{aligned}$$



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.

# $Z_N$ multicomponent scalar scenarios

It may be that the DM is actually composed of several species (as the visible sector):  $\Omega_{DM} = \Omega_{\chi_1} + \Omega_{\chi_2} + \dots$

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.

## $Z_4$ scalar model: interactions

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

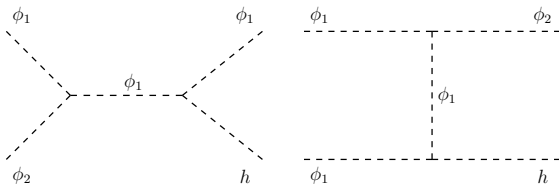
$$\phi_1 \sim \omega_4, \quad \phi_2 \sim \omega_4^2; \quad \omega_4 = \exp(i2\pi/4).$$

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

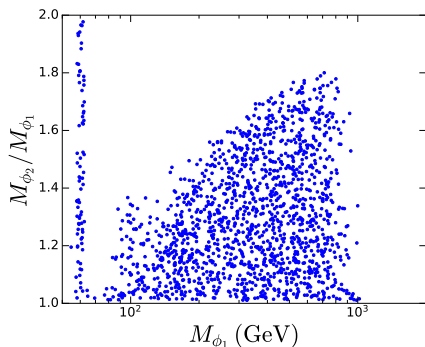
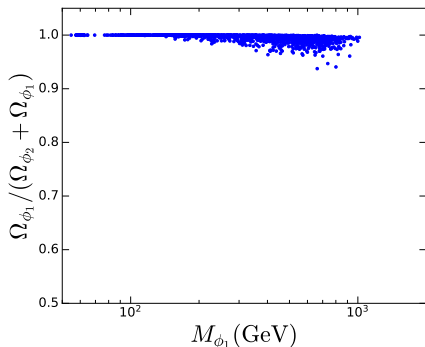
$\langle \phi_{1,2} \rangle = 0$  and  $M_2 < 2M_1$  so that  $\phi_2$  remains stable.

Set of free parameters:

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



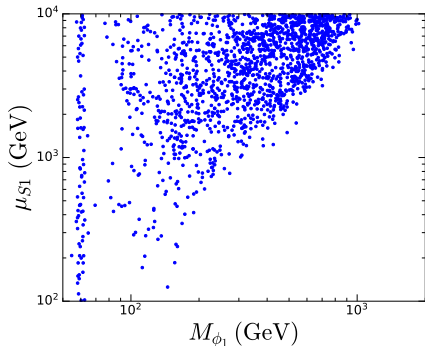
## $Z_4$ model: $M_{\phi_1} < M_{\phi_2}$



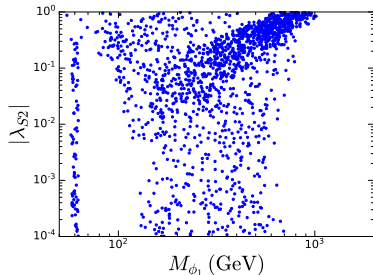
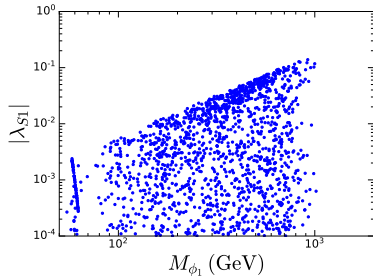
- $\phi_1$  always gives the dominant contribution (more than 90% of  $\Omega_{DM}$ ).
- This hierarchy is a consequence of the new  $Z_4$  interactions, which tend to suppress  $\Omega$  of the heavier particle more than that of the lighter one.
- The masses are not required to be degenerate.



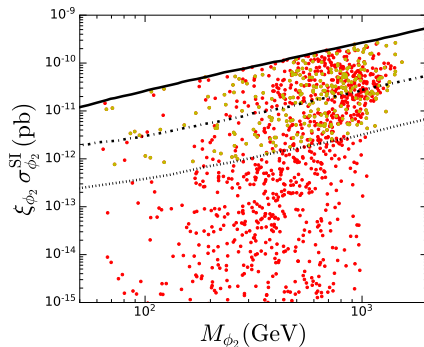
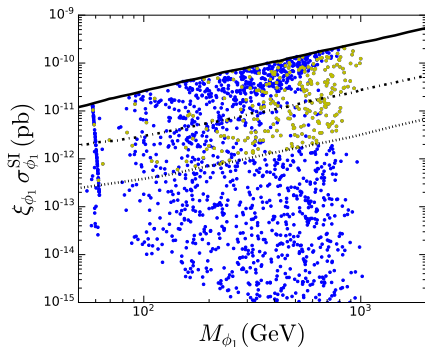
## $Z_4$ scalar model: $M_{\phi_1} < M_{\phi_2}$



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



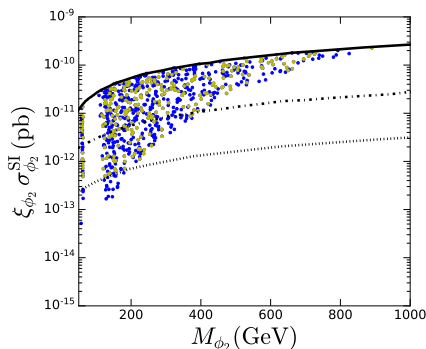
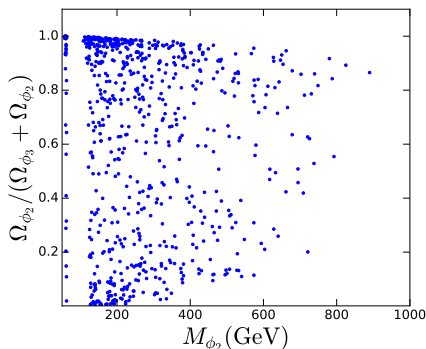
# Direct detection: $M_{\phi_1} < M_{\phi_2}$



- Either DM particle may be observed in future DD experiments.
- The small  $\Omega_2$  can be compensated by a large  $\lambda_{S2}$ .
- Yellow points indicate that both DM particles lay within DARWIN.

# A $Z_6$ model

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



- Thanks to the semi-annihilation processes the mass range below 1 TeV turns out to be viable.  $\phi_2 + \phi_2 \rightarrow \phi_2^* + h$ .
- Both particles may contribute significantly.
- $M_3/M_2$  varies over a wide range: they are not required to be degenerate.
- The detection of  $\phi_2$  at DARWIN is practically guaranteed.

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

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

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

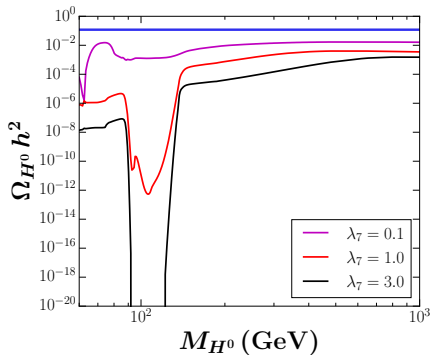
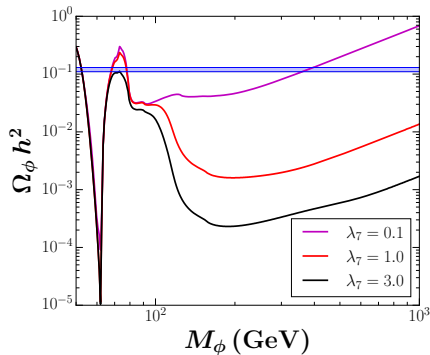
Free parameters:  $\lambda_{S1}, \lambda_L, \lambda_6, \lambda_7, M_\phi, M_{H^0}, M_{H^\pm}$ .

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

$\phi$ Processes	Type	$H^0$ Processes	Type
$\phi + \phi^\dagger \rightarrow SM + SM$	1100	$H^0 + H^{0\dagger} \rightarrow SM + SM$	2200
$\phi + \phi^\dagger \rightarrow H^0 + H^{0\dagger}$	1122	$H^0 + H^{0\dagger} \rightarrow \phi + \phi^\dagger$	2211
$\phi + \phi \rightarrow H^0 + h(Z), H^\pm + W^\mp$	1120	$H^0 + h \rightarrow \phi + \phi$	2011
		$H^{0\dagger} + \phi \rightarrow \phi^\dagger + h(Z)$	2110

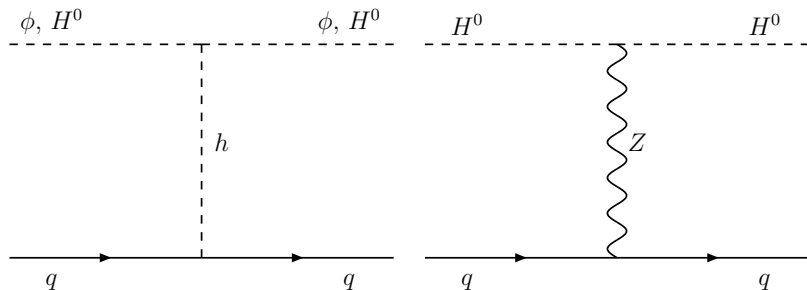
# Parameter dependence: DM semiannihilation

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



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

# Direct detection



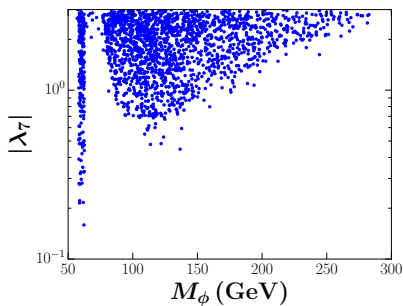
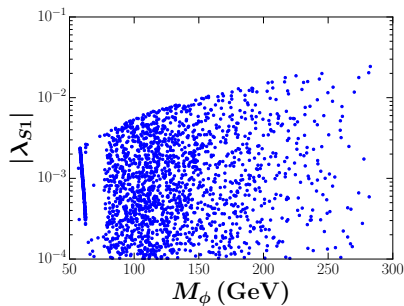
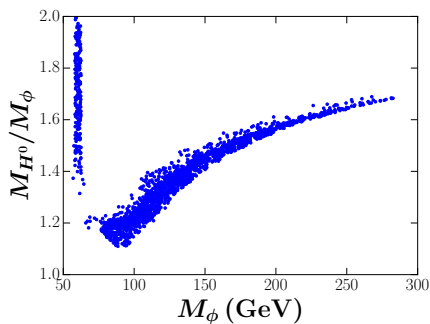
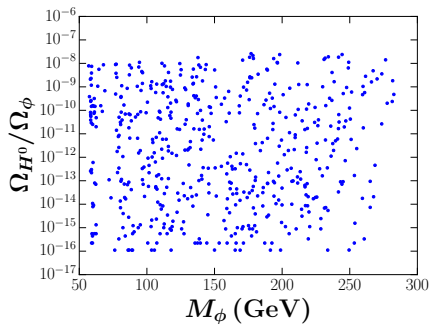
$$\sigma_N^{\text{SI}} = \frac{\mu_N^2}{\pi} \frac{[Z(f_p^S + f_p^V) + (A - Z)(f_n^S + f_n^V)]^2}{A^2},$$

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

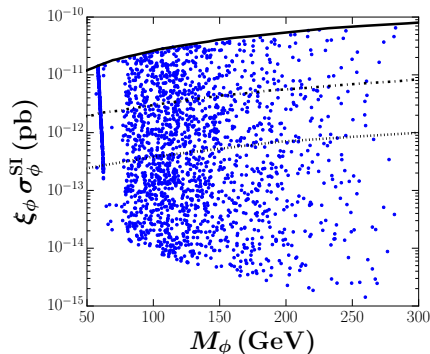
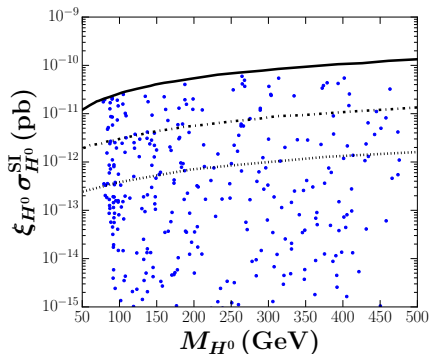
$$\sigma_{H^0} \approx \frac{G_F^2}{2\pi} \frac{\mu_N^2}{A^2} [(A - Z) - Z(1 - 4s_W^2)]^2 = 2 \times 10^{-3} \text{ pb}. \quad (1)$$

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.

# Viable parameter space



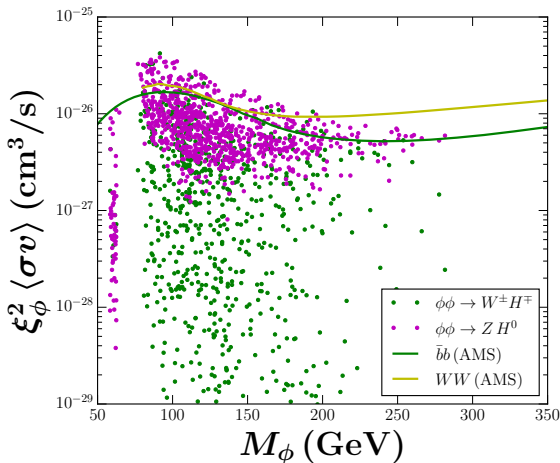
# Direct detection



- Either DM particle may be observed in future DD experiments.
- Sizeable  $\sigma_{H_0}$  is compensated by a large suppression on  $\Omega_{H_0}$ .



# Indirect detection



- The most relevant channels are  $\phi + \phi \rightarrow W^\pm + H^\mp, Z + H^0$ .
- AMS antiproton data is starting to probe this model.

# Concluding remarks

- ① Viable  $Z_N$  models within the golden range of DM masses 100-1000 GeV.
- ② The semi-annihilation processes play an essential role in setting the DM abundances.
- ③ 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 further implications such as neutrino masses, phase transitions, etc.

THANK YOU