Complex scalar dark matter from the gauged two Higgs doublet model

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New Physics with Exotic and Long-Lived Particles
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Overview

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- Matter content of the G2HDM
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- Methodology
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  - Goldstone boson-like DM
- Summary

Motivation

A few years after the discovery of the Higgs boson, we can still ask some questions

- is it *"the"* Higgs or is it *"a"* Higgs?
- What about dark matter candidates?
- And neutrino masses (oscillation)?
- Are there any extra symmetries?

A popular class of models that aims to solve some of these problems is the two Higgs doublet model.

Motivation: Two Higgs Doublet models

Simple extensions that explain BSM physics

- MSSM: 2 Higgs doublets due to superpotential.
- 2HDM: the prototype, extra CP phases.
- IHDM: dark matter candidate, no FCNC at tree level.
- G2HDM: more details ahead...

Gauged 2 Higgs Doublet Model (G2HDM)

Main feature: the two Higgs doublets are embedded in a doublet of an extra $SU(2)_H$

- ✓ New gauge group $SU(2)_H \times U(1)_X$
- ✓ This approach simplifies the potential for the doublets.
- ✓ The additional complex vector fields are neutral
- ✓ Anomaly free through the addition of heavy fermions.
- ✓ One of the Higgs can be inert $\longrightarrow$ DM candidate.
- ! The cost is the introduction of new scalars: An $SU(2)_H$ triplet and a doublet.

Gauged 2 Higgs Doublet Model (G2HDM)

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$H = (H_1 \quad H_2)^T$	1	2	2	1/2	1
$\Delta_H = \begin{pmatrix} \frac{\Delta_3}{2} & \frac{\Delta_p}{\sqrt{2}} \\ \frac{\Delta_m}{\sqrt{2}} & -\frac{\Delta_3}{2} \end{pmatrix}$	1	1	3	0	0
$\Phi_H = (\Phi_1 \quad \Phi_2)^T$	1	1	2	0	1

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix},$$

$$\Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi+\phi_2}{\sqrt{2}} + i\frac{G_H^0}{\sqrt{2}} \end{pmatrix}, \quad \Delta_H = \begin{pmatrix} \frac{-v_\Delta+\delta_3}{2} & \frac{1}{\sqrt{2}}\Delta_p \\ \frac{1}{\sqrt{2}}\Delta_m & \frac{v_\Delta-\delta_3}{2} \end{pmatrix}.$$

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VEVS

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Charged Higgs

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$\mathcal{Z}_2$-odd neutral scalars

Matter content of the G2HDM

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$Q_L = (u_L \;\; d_L)^T$	3	2	1	1/6	0
$U_R = \left(u_R \;\; u_R^H\right)^T$	3	1	2	2/3	1
$D_R = \left(d_R^H \;\; d_R\right)^T$	3	1	2	$-1/3$	-1
u_L^H	3	1	1	2/3	0
d_L^H	3	1	1	$-1/3$	0
$L_L = (\nu_L \;\; e_L)^T$	1	2	1	$-1/2$	0
$N_R = \left(\nu_R \;\; \nu_R^H\right)^T$	1	1	2	0	1
$E_R = \left(e_R^H \;\; e_R\right)^T$	1	1	2	-1	-1
ν_L^H	1	1	1	0	0
e_L^H	1	1	1	-1	0

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$U_R = \left(u_R \;\; u_R^H\right)^T$	3	1	2	2/3	1
$D_R = \left(d_R^H \;\; d_R\right)^T$	3	1	2	$-1/3$	-1
u_L^H	3	1	1	2/3	0
d_L^H	3	1	1	$-1/3$	0
$L_L = (\nu_L \;\; e_L)^T$	1	2	1	$-1/2$	0
$N_R = \left(\nu_R \;\; \nu_R^H\right)^T$	1	1	2	0	1
$E_R = \left(e_R^H \;\; e_R\right)^T$	1	1	2	-1	-1
ν_L^H	1	1	1	0	0
e_L^H	1	1	1	-1	0

Accidental $\mathcal{Z}_2$ symmetry

For example, take a look at the potential

$$\mu_H^2\left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_H\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 + \lambda_H'\left(-H_1^\dagger H_1 H_2^\dagger H_2 + H_1^\dagger H_2 H_2^\dagger H_1\right)$$

$$\mu_\Phi^2\left(\Phi_1^*\Phi_1 + \Phi_2^*\Phi_2\right) + \lambda_\Phi\left(\Phi_1^*\Phi_1 + \Phi_2^*\Phi_2\right)^2$$

$$-\mu_\Delta^2\left(\frac{1}{2}\Delta_3^2 + \Delta_p\Delta_m\right) + \lambda_\Delta\left(\frac{1}{2}\Delta_3^2 + \Delta_p\Delta_m\right)^2$$

$$+ M_{H\Delta}\left(\frac{1}{\sqrt{2}}H_1^\dagger H_2\Delta_p + \frac{1}{2}H_1^\dagger H_1\Delta_3 + \frac{1}{\sqrt{2}}H_2^\dagger H_1\Delta_m - \frac{1}{2}H_2^\dagger H_2\Delta_3\right)$$
$$- M_{\Phi\Delta}\left(\frac{1}{\sqrt{2}}\Phi_1^*\Phi_2\Delta_p + \frac{1}{2}\Phi_1^*\Phi_1\Delta_3 + \frac{1}{\sqrt{2}}\Phi_2^*\Phi_1\Delta_m - \frac{1}{2}\Phi_2^*\Phi_2\Delta_3\right) + \cdots$$

Accidental $\mathcal{Z}_2$ symmetry

For example, take a look at the potential

$$\mu_H^2\left(\overset{+}{H_1^\dagger}\overset{+}{H_1}+\overset{-}{H_2^\dagger}\overset{-}{H_2}\right)+\lambda_H\left(\overset{+}{H_1^\dagger}\overset{+}{H_1}+\overset{-}{H_2^\dagger}\overset{-}{H_2}\right)^2+\lambda_H'\left(-\overset{+}{H_1^\dagger}\overset{+}{H_1}\overset{-}{H_2^\dagger}\overset{-}{H_2}+\overset{+}{H_1^\dagger}\overset{-}{H_2}\overset{-}{H_2^\dagger}\overset{+}{H_1}\right)$$

$$\mu_\Phi^2\left(\overset{-}{\Phi_1^*}\overset{-}{\Phi_1}+\overset{+}{\Phi_2^*}\overset{+}{\Phi_2}\right)+\lambda_\Phi\left(\overset{-}{\Phi_1^*}\overset{-}{\Phi_1}+\overset{+}{\Phi_2^*}\overset{+}{\Phi_2}\right)^2$$

$$-\mu_\Delta^2\left(\frac{1}{2}\overset{+^2}{\Delta_3^2}+\overset{-}{\Delta_p}\overset{-}{\Delta_m}\right)+\lambda_\Delta\left(\frac{1}{2}\overset{+^2}{\Delta_3^2}+\overset{-}{\Delta_p}\overset{-}{\Delta_m}\right)^2$$

$$+\,M_{H\Delta}\left(\frac{1}{\sqrt{2}}\overset{+}{H_1^\dagger}\overset{-}{H_2}\overset{-}{\Delta_p}+\frac{1}{2}\overset{+}{H_1^\dagger}\overset{+}{H_1}\overset{+}{\Delta_3}+\frac{1}{\sqrt{2}}\overset{-}{H_2^\dagger}\overset{+}{H_1}\overset{-}{\Delta_m}-\frac{1}{2}\overset{-}{H_2^\dagger}\overset{-}{H_2}\overset{+}{\Delta_3}\right)$$

$$-\,M_{\Phi\Delta}\left(\frac{1}{\sqrt{2}}\overset{-}{\Phi_1^*}\overset{+}{\Phi_2}\overset{-}{\Delta_p}+\frac{1}{2}\overset{-}{\Phi_1^*}\overset{-}{\Phi_1}\overset{+}{\Delta_3}+\frac{1}{\sqrt{2}}\overset{+}{\Phi_2^*}\overset{-}{\Phi_1}\overset{-}{\Delta_m}-\frac{1}{2}\overset{+}{\Phi_2^*}\overset{+}{\Phi_2}\overset{+}{\Delta_3}\right)+\cdots$$

and so on

$\mathcal{Z}_2$-odd fields

$\mathcal{Z}_2$-odd complex scalars mass matrix $\left(\text{basis } \left\{G_H^p, H_2^{0*}, \Delta_p\right\}\right)$

$$\begin{pmatrix} M_{\Phi\Delta} v_\Delta + \frac{1}{2}\lambda'_{H\Phi} v^2 & \frac{1}{2}\lambda'_{H\Phi} v v_\Phi & -\frac{1}{2} M_{\Phi\Delta} v_\Phi \\ \frac{1}{2}\lambda'_{H\Phi} v v_\Phi & M_{H\Delta} v_\Delta + \frac{1}{2}\lambda'_{H\Phi} v_\Phi^2 & \frac{1}{2} M_{H\Delta} v \\ -\frac{1}{2} M_{\Phi\Delta} v_\Phi & \frac{1}{2} M_{H\Delta} v & \frac{1}{4 v_\Delta}\left(M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) \end{pmatrix}$$

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$v_\Phi \geq v_\Delta$

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After diagonalization we have

1. $\widetilde{G}^p$: massless
2. D: lighter
3. $\widetilde{\Delta}$: heavier

Lightest $\mathcal{Z}_2$-odd complex scalar

with $\mathcal{O}^D$ such that

$$\{G_H^p, H_2^{0*}, \Delta_p\}^{\mathrm{T}} = \mathcal{O}^D \cdot \{\widetilde{G}^p, D, \widetilde{\Delta}\}^{\mathrm{T}}$$

we can write the linear combination D as

$$D = \mathcal{O}_{12}^D G_H^p + \mathcal{O}_{22}^D H_2^{0*} + \mathcal{O}_{32}^D \Delta_p \ .$$

Using this expression we can distinguish three types of DM:

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3. Goldstone boson-like DM for $\left(O_{12}^D\right)^2 \equiv f_{G^p} > 2/3$

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Other relevant $\mathcal{Z}_2$-odd particles

Other $\mathcal{Z}_2$-odd particles that affect the calculation presented here are:

1. the charged Higgs $H^{\pm}$.
2. the massive $SU(2)_H$ gauge boson W'.
3. the heavy fermions f^H.

- On the parameter space: All of them need to be heavier than D.
- On the relic density: All of them may coannihilate with D if their mass is close to m_D.

Other relevant $\mathcal{Z}_2$-odd particles

The charged Higgs mass

$$m_{H^\pm}^2 = M_{H\Delta} v_\Delta - \frac{1}{2}\lambda'_H v^2 + \frac{1}{2}\lambda'_{H\Phi} v_\Phi^2 \; .$$

is very close to the (2,2) element in the mass matrix corresponding to H_2^0

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It differs only by $-\lambda'_H v^2/2$

Other relevant $\mathcal{Z}_2$-odd particles

The charged Higgs mass

$$m^2_{H^\pm} = M_{H\Delta} v_\Delta \boxed{- \frac{1}{2}\lambda'_H v^2} + \frac{1}{2}\lambda'_{H\Phi} v^2_\Phi \ .$$

is very close to the (2,2) element in the mass matrix corresponding to H^0_2

It differs only by $-\lambda'_H v^2/2$

- This may affect the **doublet-like DM case**.

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- If this term is very negative, $H^\pm$ may become lighter than D.

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- This may affect the **doublet-like DM case**.
- If this term is very negative, $H^\pm$ may become lighter than D.
- We also expect some amount of coannihilation with $H^\pm$ in the doublet-like DM case.

Other relevant $\mathcal{Z}_2$-odd particles

The massive gauge boson W' has a mass

$$m_{W'}^2 = \frac{1}{4} g_H^2 \left(v^2 + v_\Phi^2 + 4 v_\Delta^2 \right).$$

To ensure that D is always lighter than W' we need to set a lower bound on g_H such that $m_D < m_{W'}$:

$$g_{H\min} = \frac{2 m_D}{\sqrt{v^2 + v_\Phi^2 + 4 v_\Delta^2}}.$$

but at the same time we will require that $g_H < 0.1$ to avoid problems with constraints in the gauge sector.

- For heavy DM, where g_H does not have much freedom, we expect to see coannihilation with W'.

Other relevant $\mathcal{Z}_2$-odd particles

Heavy fermions receive mass from the Yukawa terms with the scalar Φ_H

$$m_{f^H} = \frac{y_{f^H} v_\Phi}{\sqrt{2}}$$

- for this study want them to be **always heavier than DM**.
- We also want to **avoid coannihilation** as much as possible:
  - They are **too many** and their added effects my cover other interesting effects
- We also want to make sure that they are **heavy enough to not be produced at current and past colliders**.

We choose the Yukawa coupling according to

$$y_{f^H} = \sqrt{2}\,\max\left[\frac{1.5\ \text{TeV}}{v_\Phi}, \min\left(\frac{1.2 m_D}{v_\Phi},\ \frac{1}{\sqrt{2}}\right)\right]\ .$$

Methodology

We start from previous studies on the G2HDM, namely:

- scalar sector theoretical and phenomenological constraints [Arhrib et al., arXiv:1806.05632] and

    1. Vacuum stability
    2. Perturbative unitarity
    3. Higgs mass and diphoton decay

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- scalar sector theoretical and phenomenological constraints [Arhrib et al., arXiv:1806.05632] and
- gauge sector contraints [Huang et al., arXiv:1905.02396]
  1. Z boson mass and decays
  2. Drell-Yan
  3. Contact interactions $e^+e^-\bar{f}f$
  4. Z' bosons searches

Methodology

We start from previous studies on the G2HDM, namely:

- scalar sector theoretical and phenomenological constraints [Arhrib et al., arXiv:1806.05632] and
- gauge sector contraints [Huang et al., arXiv:1905.02396]

To which we collectively refer as scalar and gauge sector constraints (SGSC).

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To which we collectively refer as scalar and gauge sector constraints (SGSC).
We collect several million points that follow the constraints described in the works refereced above. This points include

- scalar potential parameters,
- gauge sector couplings,
- scalar and gauge bosons masses and mixings.

Methodology

We pass this points to `micrOMEGAs` [Bélanger et al., arXiv:1801.03509] to calculate

- relic density
- direct detection cross sections,
- averaged annihilation cross sections times velocity,
- Annihilation channels fractions at freeze-out time and current time,

Lastly, we pass the annihilation channels fraction annihilation cross section at current time to `LikeDM` [Huang et al., arXiv:1603.07119] to calculate ID likelihood from Fermi-LAT pass 8 data.

Isospin violation and Xenon detectors

Experiments report and isospin conserving nucleon-DM elastic scattering cross section

To take account of isospin violation (ISV) effects, we calculate this cross section in the nucleus level.

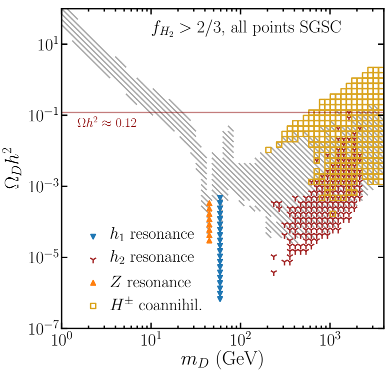
$$\sigma_{D\mathcal{N}} = \frac{4\mu_{\mathcal{A}}^2}{\pi}\left[f_p \mathcal{Z} + f_n(\mathcal{A} - \mathcal{Z})\right]^2,$$

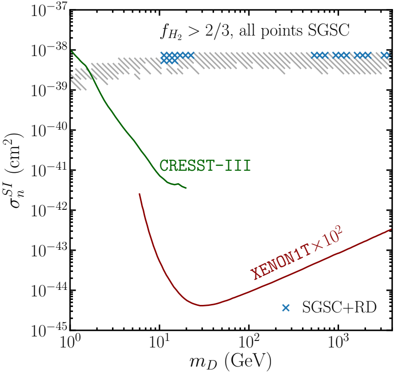
The actual limit for XENON1T in this case is rescaled like

$$\sigma_{D\mathcal{N}}^{\mathrm{X1T}} = \sigma_p^{\mathrm{SI}}(\mathrm{X1T}) \times \mathcal{A}^2 \times \frac{\mu_{\mathcal{A}}^2}{\mu_p^2},$$

Note that for $f_n/f_p = -\mathcal{Z}/(\mathcal{A} - \mathcal{Z}) \approx -0.7$ (Xe) the terms in $\sigma_{D\mathcal{N}}$ cancel

Doublet-like DM





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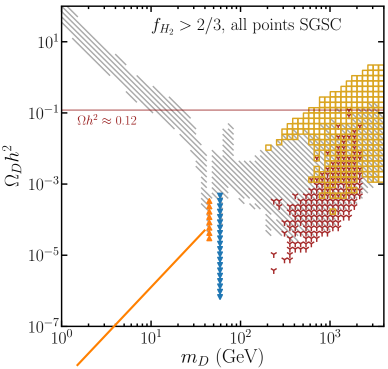
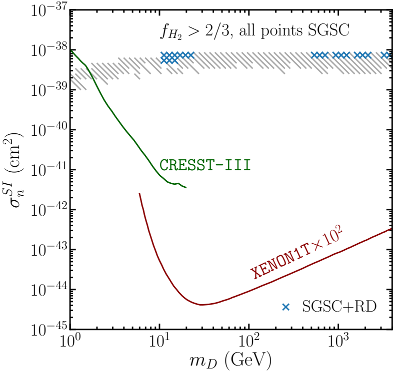


Z resonance



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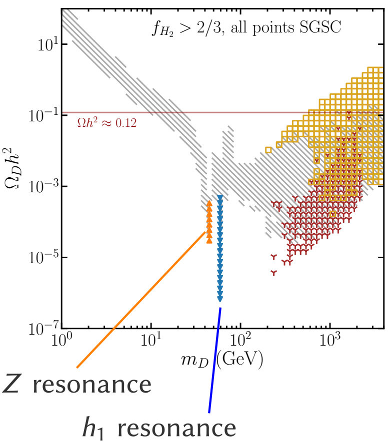

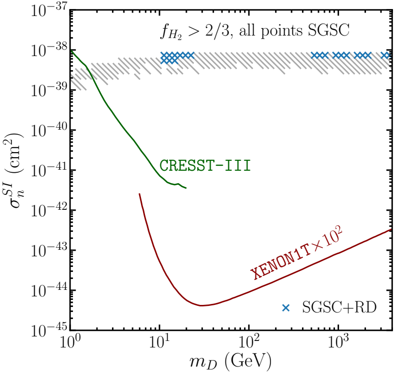

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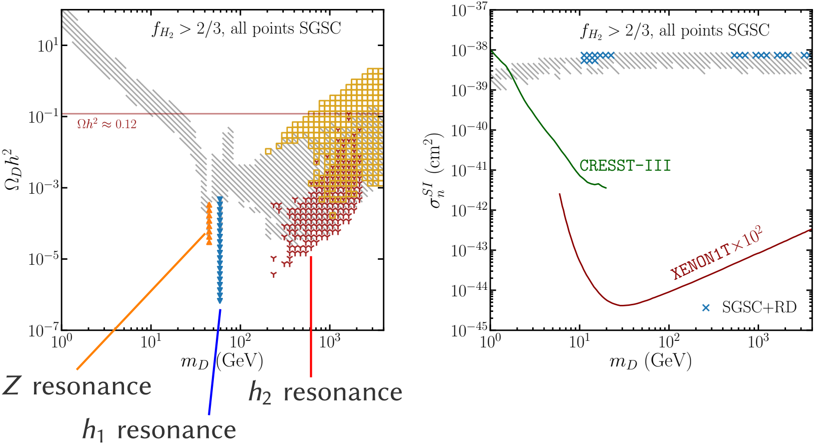

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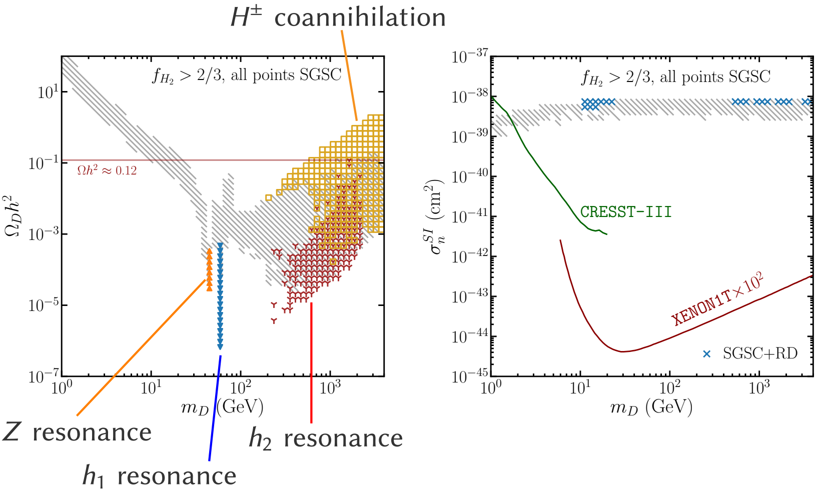

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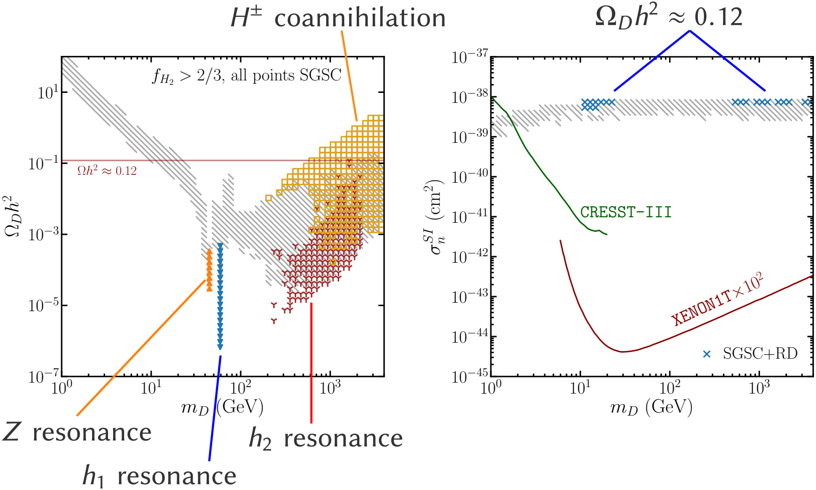

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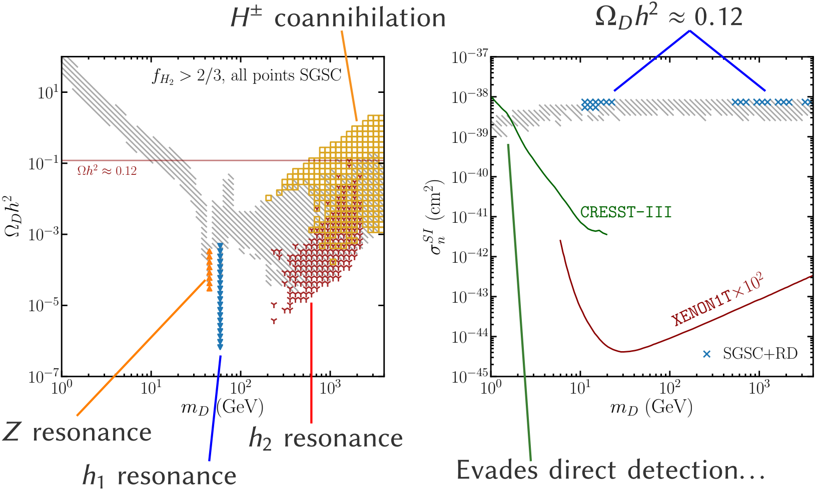

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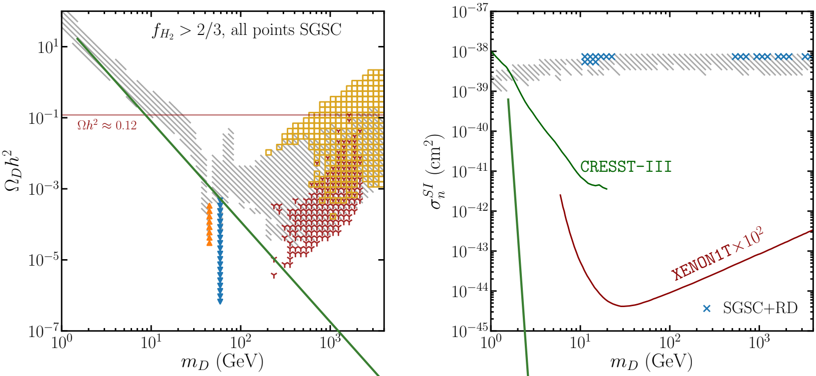
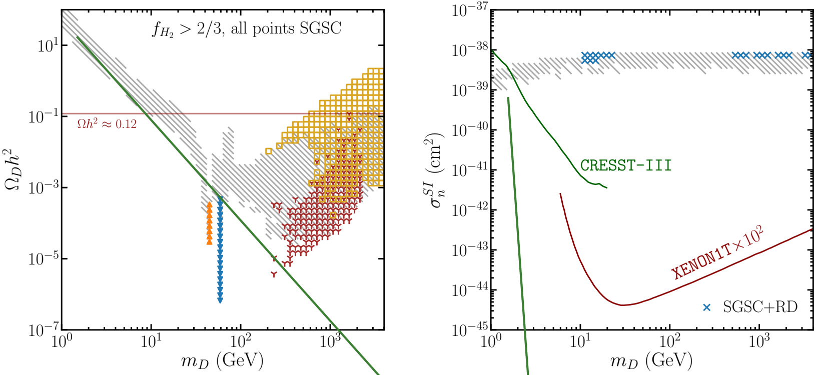


Evades direct detection…

…but $\Omega_D h^2$ is too large

Doublet-like DM



Evades direct detection…

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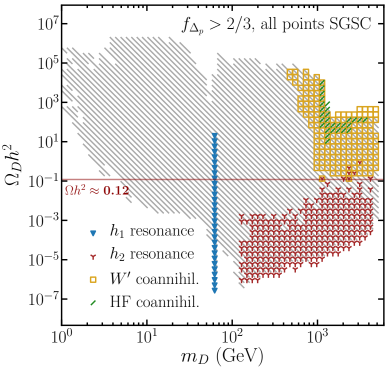
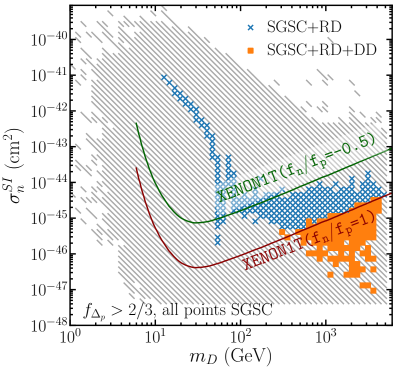
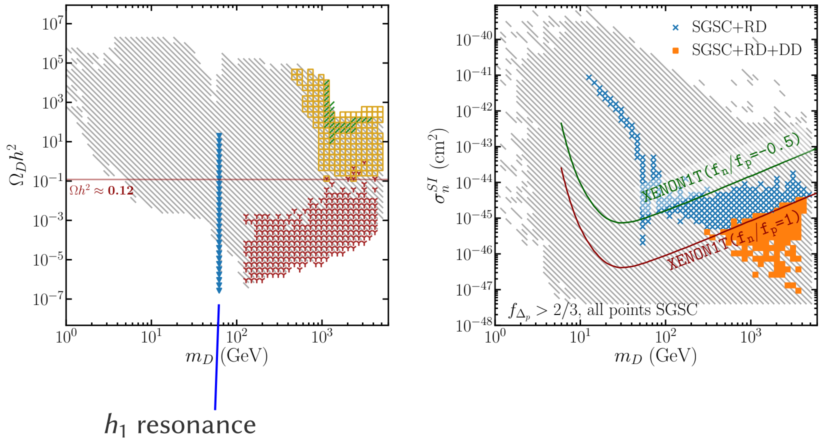
We can conclude that doublet-like DM is **ruled out** for this study.

Triplet-like DM





Triplet-like DM



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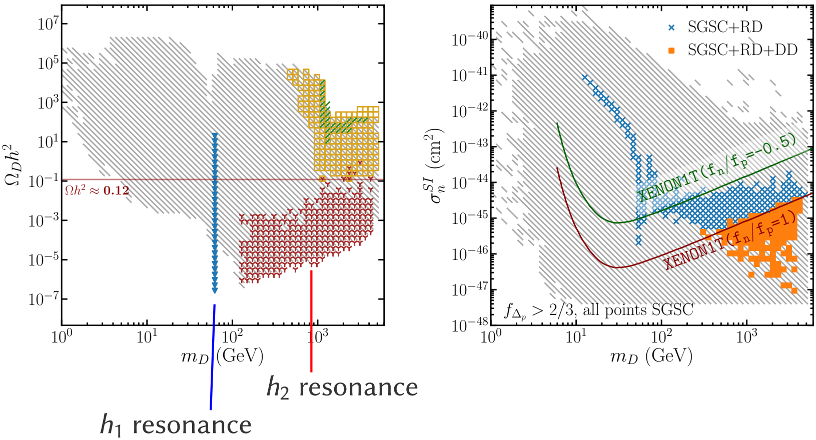

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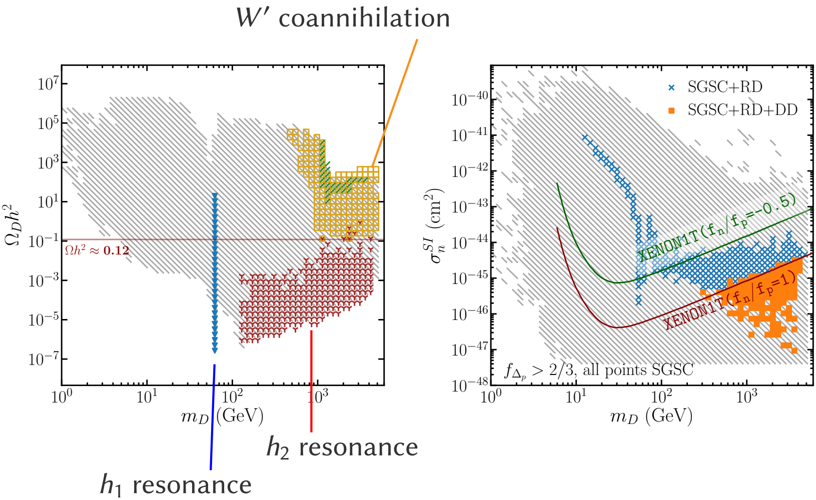

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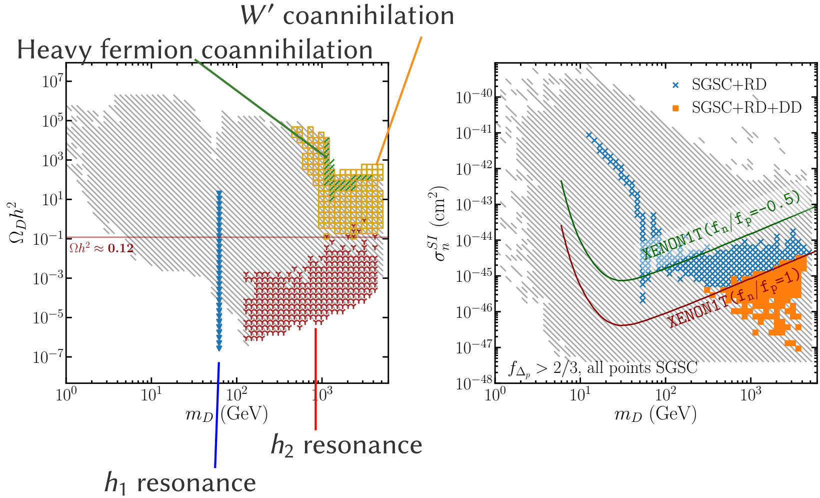

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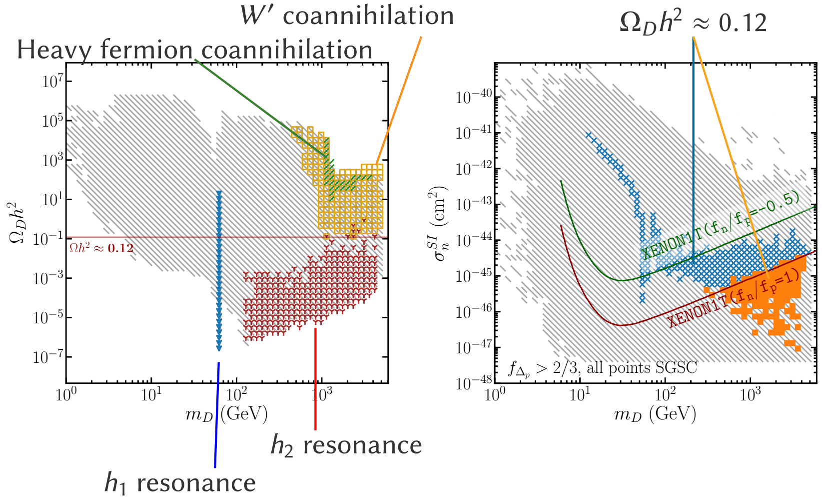

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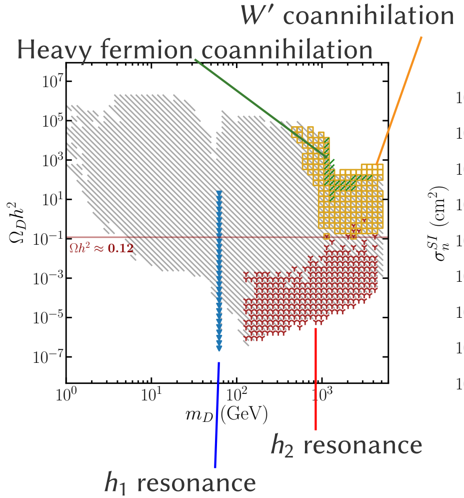

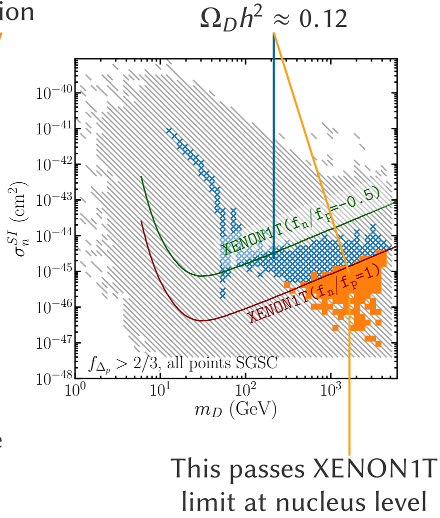

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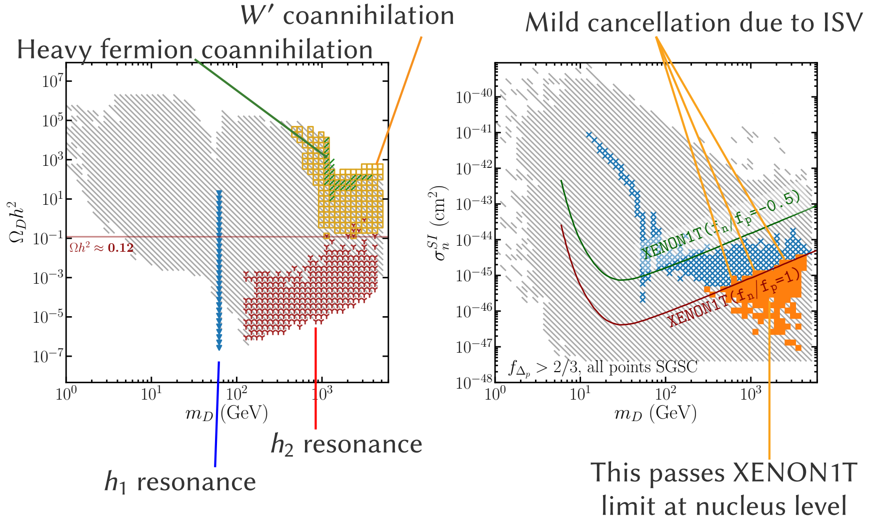

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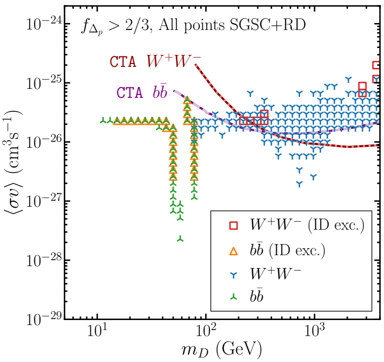

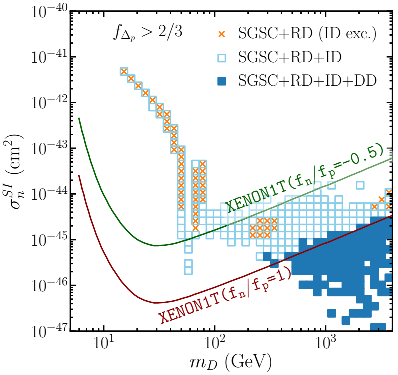

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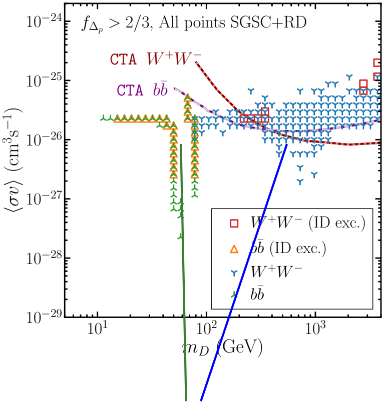
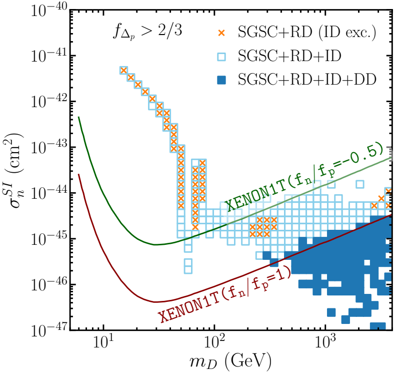
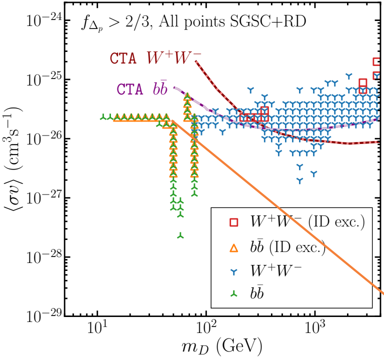
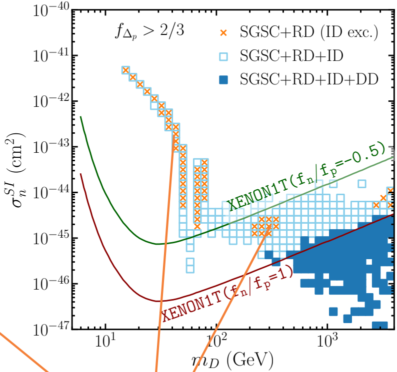




Present time: Annihilation mostly to $b\bar{b}$ and W^+W^-

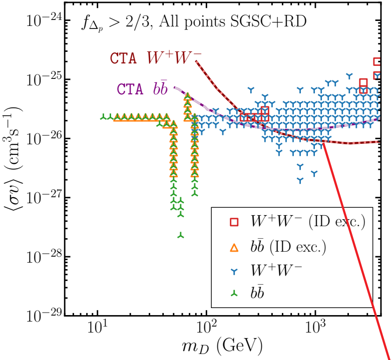
Triplet-like DM

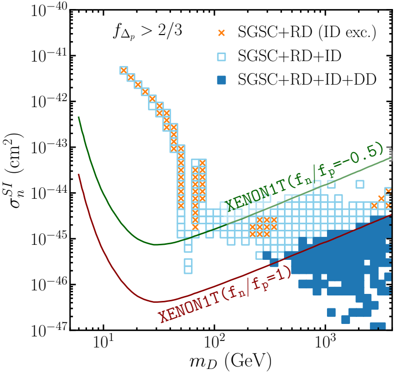




Most ID exclusions happens
in regions excluded by DD

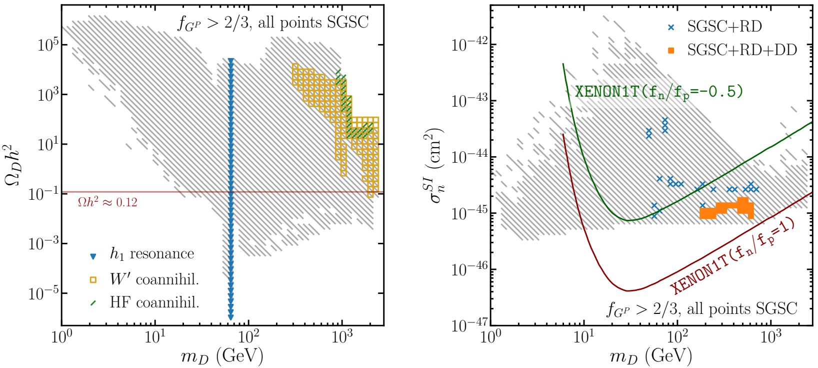
Triplet-like DM





CTA may further constraint
the heavier DM region

Goldstone boson-like DM



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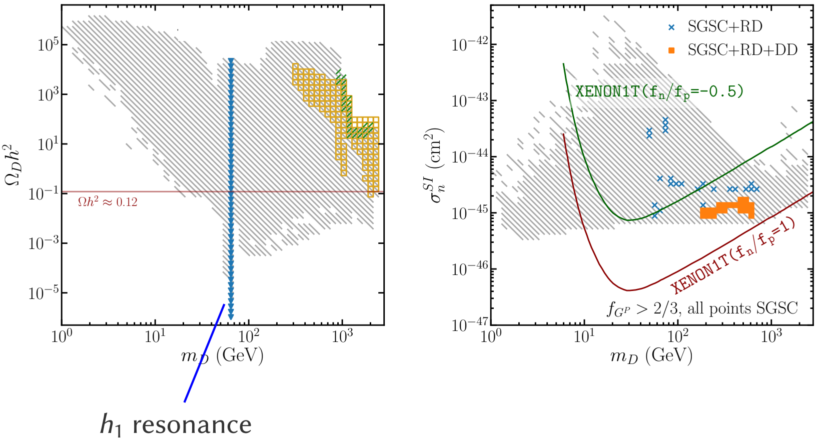
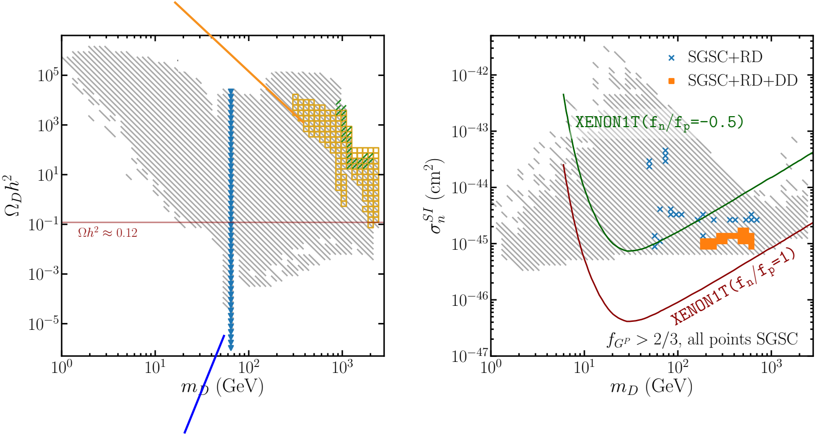


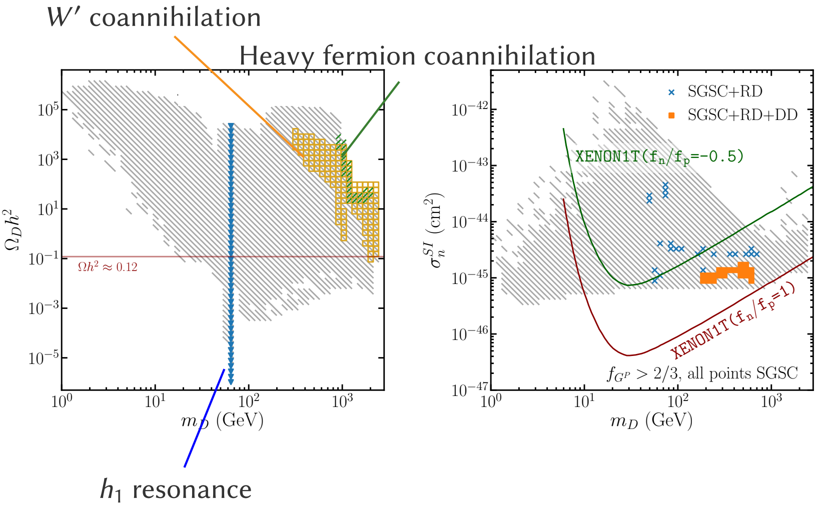
Goldstone boson-like DM

W' coannihilation

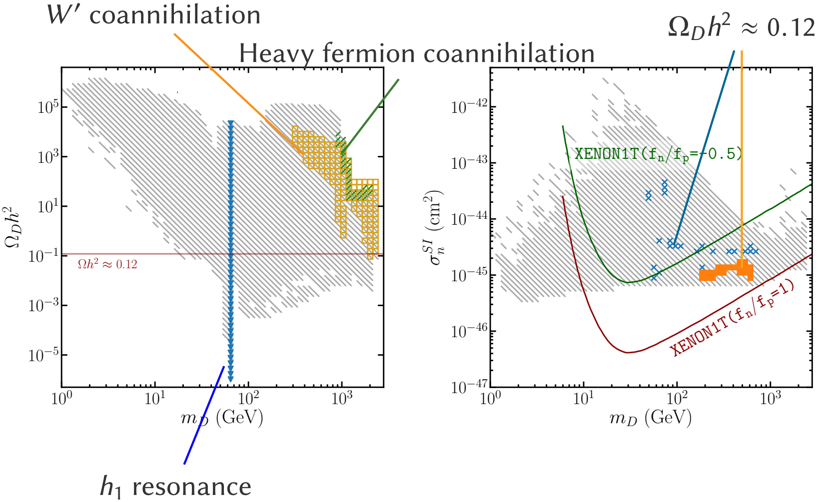


h_1 resonance

Goldstone boson-like DM



Goldstone boson-like DM

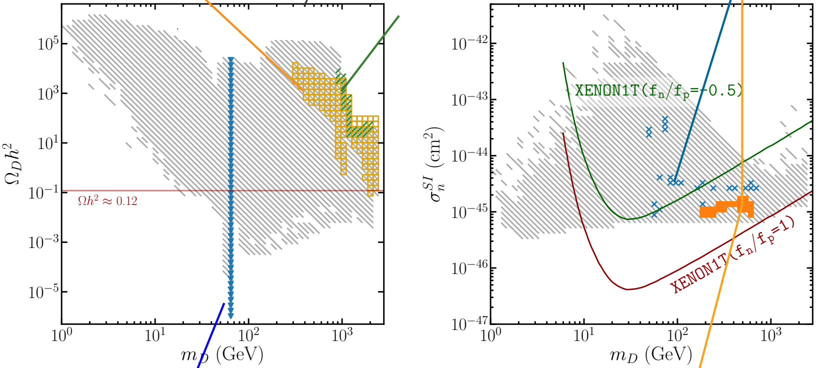


Goldstone boson-like DM

W' coannihilation

Heavy fermion coannihilation

$\Omega_D h^2 \approx 0.12$



h_1 resonance

This passes XENON1T limit at nucleus level, thanks to ISV, but it is fine-tuned

Summary

- The G2HDM is a new framework with a rich but simple scalar sector.
- The extended gauge group results in an accidental $\mathcal{Z}_2$ symmetry that keeps DM stable.
- It is possible to recognize three main types of complex scalar dark matter according to their composition.
- The DM dominated by $\Delta_{(p,m)}$ (triplet-like) has the largest region passing both relic density and direct detection constraints.
- The DM dominated by G_H^p (Goldstone boson-like) can pass all the constraints considered here but requires fine-tuned ISV with $f_n/f_p \approx -0.7$.
- There are other possible DM candidates besides the ones presented here: The W' gauge boson and the new heavy neutrinos