# A global study of the extended scalar singlet model

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## Introduction

- A net imbalance between matter (baryons) and antimatter (anti-baryons) number densities as

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 10^{-10}. \quad (1)$$

- Theories of baryogenesis try to dynamically generate the asymmetry from symmetric initial conditions in the early universe.
- Electroweak baryogenesis (EWBG): baryogenesis via a strong first-order electroweak phase transition (EWPT) around $T \sim 100$ GeV.
- With $m_h = 125$ GeV, EWPT is *not* first-order in the Standard Model (SM) $\to$ require new physics beyond the SM (BSM).
- A simple $\mathbb{Z}_2$ symmetric scalar Higgs portal *cannot* simultaneously account for the observed dark matter (DM) abundance and matter-antimatter asymmetry.
- We study the phenomenology of the extended scalar singlet model with a fermionic DM candidate.

## Singlet fermion dark matter model

- Introduce a new real scalar singlet $S$ and a Dirac fermion DM field $\psi$ via

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_S + \mathcal{L}_\psi + \mathcal{L}_{\rm portal}, \quad (2)$$

where $\mathcal{L}_{\rm SM}$ is the SM Lagrangian,

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{3}\mu_3 S^3 - \frac{1}{4}\lambda_S S^4, \quad (3)$$

$$\mathcal{L}_\psi = \overline{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi - g_S \overline{\psi}\psi S, \quad (4)$$

$$\mathcal{L}_{\rm portal} = -\mu_{\Phi S}\Phi^\dagger \Phi S - \frac{1}{2}\lambda_{\Phi S}\Phi^\dagger\Phi S^2. \quad (5)$$

- A linear term $\mu_1^3 S$ is removed by a constant shift $S \to S + \sigma$.
- Both $\phi \equiv \langle \Phi^0 \rangle$ and $S$ can acquire non-zero VEVs. We define them as

$$\langle \phi \rangle \equiv v_0 = 246.22\,\text{GeV}, \quad \langle S \rangle = s_0. \quad (6)$$

- After electroweak symmetry breaking (EWSB), $\mathcal{L}_{\rm portal}$ induces a mixing between $\varphi = \phi - v_0$ and $s = S - s_0 \to$ physical mass eigenstates are

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \varphi \\ s \end{pmatrix}, \quad (7)$$

where $\alpha$ is the mixing angle.
- For the tree-level potential to be bounded from below, we require

$$\lambda_\Phi > 0, \quad \lambda_S > 0, \quad \lambda_{\Phi S} > -2\sqrt{\lambda_\Phi \lambda_S}. \quad (8)$$

- After EWSB, the fermion DM Lagrangian is

$$\mathcal{L}_\psi = \overline{\psi}(i\partial\!\!\!/ - m_\psi)\psi - g_S\overline{\psi}\psi s, \quad (9)$$

where $m_\psi = \mu_\psi + g_S s_0$.
- With $m_h = 125.13$ GeV, the model contains 7 free parameters

$$m_H, \quad s_0, \quad \mu_3, \quad \lambda_S, \quad \alpha, \quad m_\psi, \quad g_S. \quad (10)$$

## Constraints

1. *Thermal relic density*: require $\Omega_\psi h^2 \leq 0.1188$ from *Planck*. Likelihood is one-sided Gaussian.
2. *Direct detection*: require $\sigma_{\rm SI}^{\rm eff} \leq \sigma_{\text{PandaX-II}}$ where $\sigma_{\rm SI}^{\rm eff}$ = effective DM-nucleon cross-section and $\sigma_{\text{PandaX-II}}$ = 90% C.L. upper limit from PandaX-II. Likelihood is one-sided Gaussian.
3. *Electroweak baryogenesis*: require $v_c/T_c \geq 0.6$ where $v_c$ = Higgs VEV at the critical temperature $T_c$. Likelihood is one-sided Gaussian.
4. *Electroweak precision observables (EWPO)*: require

$$\Delta S = 0.04 \pm 0.11, \quad (11)$$
$$\Delta T = 0.09 \pm 0.14, \quad (12)$$
$$\Delta U = -0.02 \pm 0.11. \quad (13)$$

   Likelihood is a correlated 3D Gaussian.
5. *Direct Higgs searches*: constraints from the LEP, Tevatron and the LHC. Likelihood is computed using the `HiggsBounds_v4.3.1` package.
6. *Higgs signal strengths*: constraints from the Higgs signal strength and mass measurements performed at the LHC. Likelihood is computed using the `HiggsSignals_v1.4.0` package.

## Preliminary results

| Parameter | Minimum | Maximum | Prior type |
|---|---|---|---|
| $m_H$ | 10 GeV | 10 TeV | log |
| $s_0$ | −1 TeV | 1 TeV | flat |
| $\mu_3$ | −1 TeV | 1 TeV | flat |
| $\lambda_S$ | $10^{-3}$ | 10 | log |
| $\alpha$ | 0 | $\pi/2$ | flat |
| $m_\psi$ | 10 GeV | 10 TeV | log |
| $g_S$ | $10^{-3}$ | 10 | log |

Table 1: Ranges and priors for the free parameters of our model.

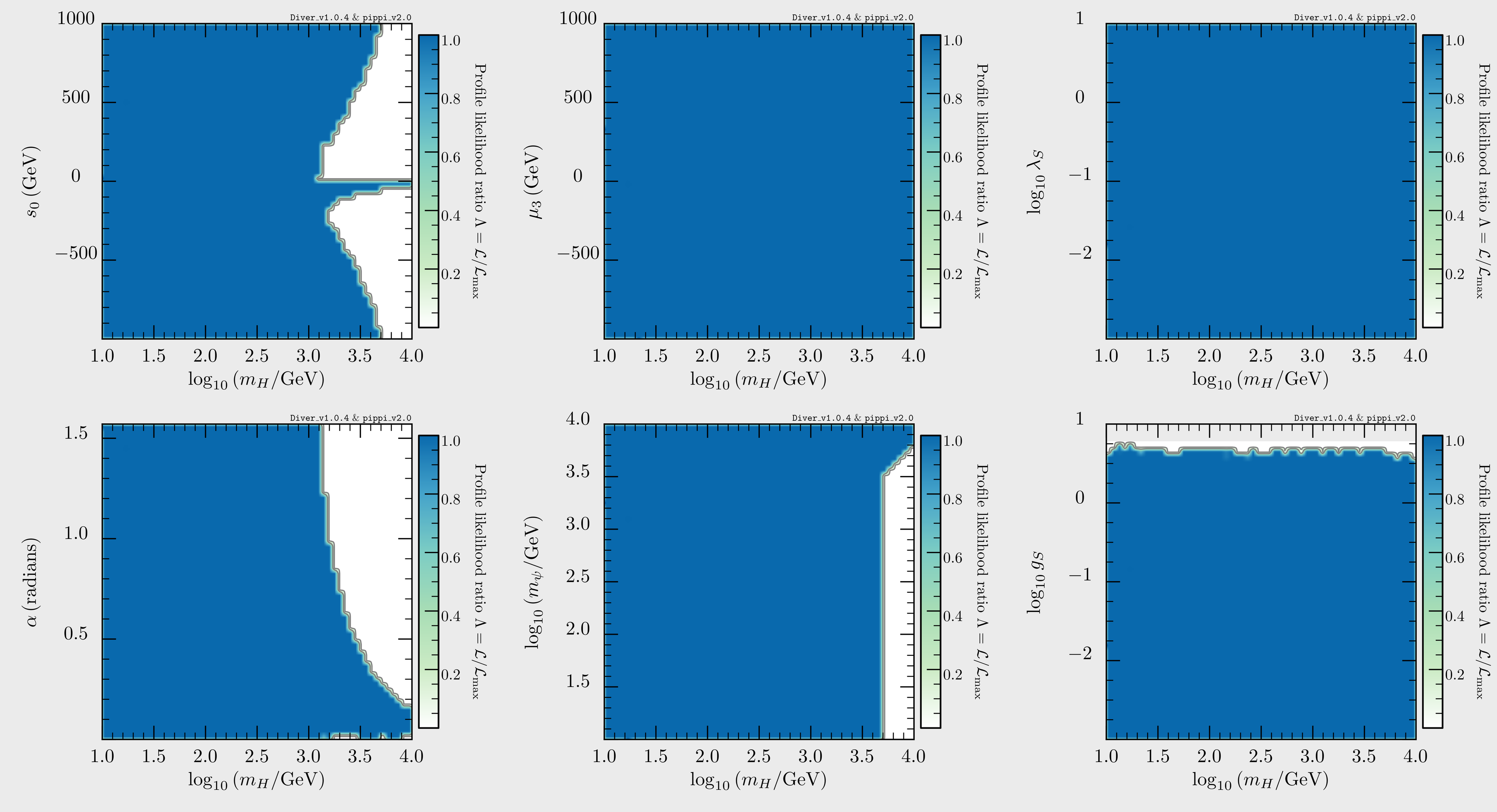

Fig. 1: 7D scan of the model parameter space using *only* the EWBG constraint.

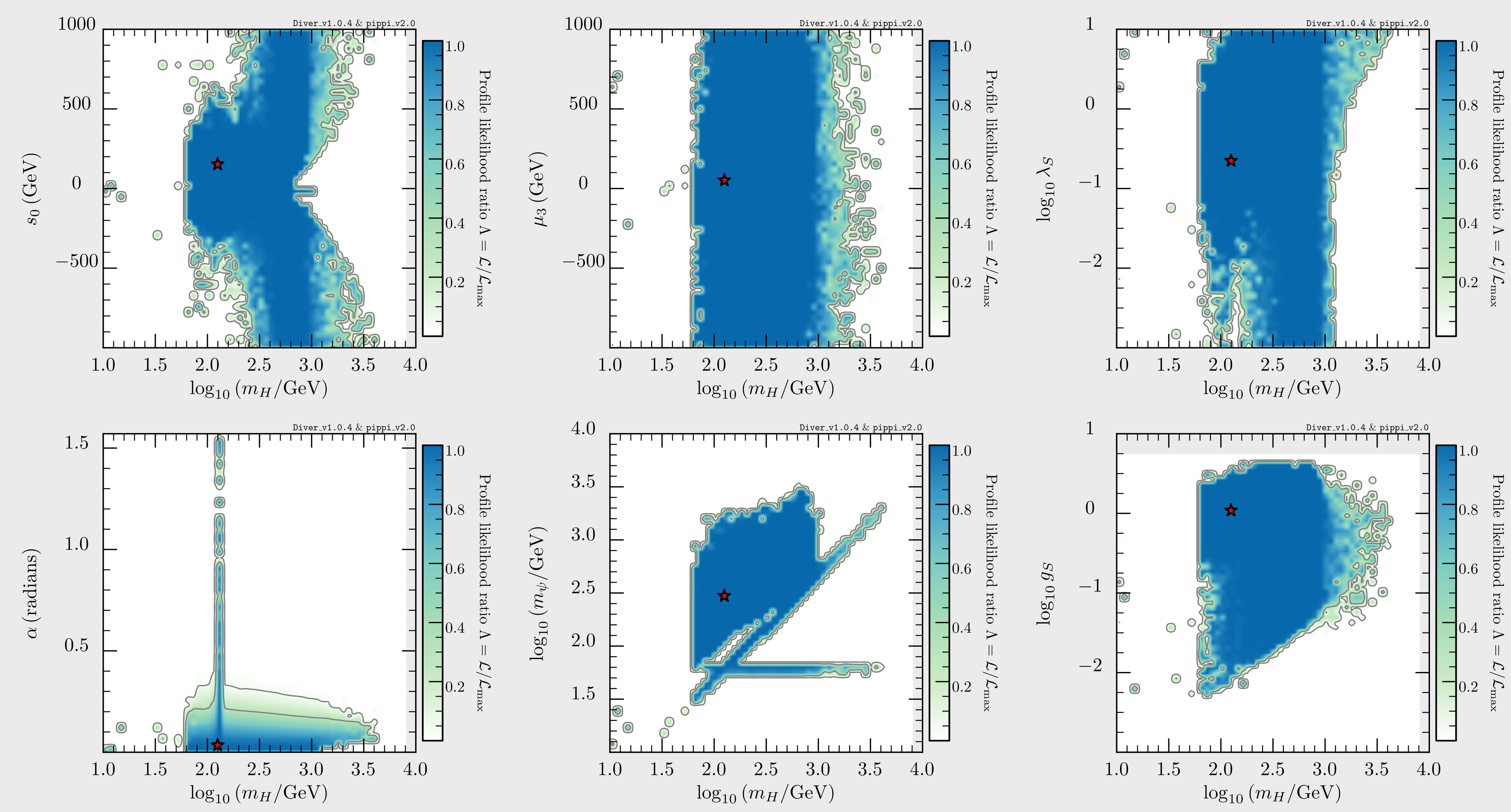

Fig. 2: 7D scan of the model parameter space using all available constraints.

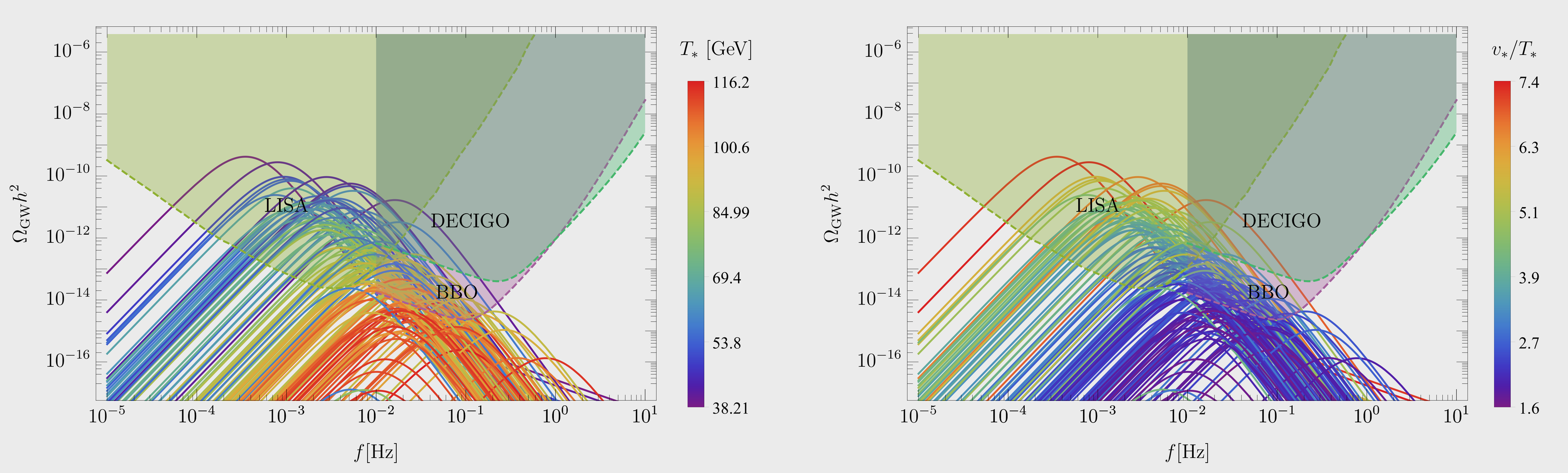


Fig. 3: Gravitational wave (GW) spectra of viable points along with the projected sensitivities of future GW experiments such as LISA, DECIGO and BBO.

## Conclusions

- A successful EWBG is viable in all parts of the model parameter space provided $g_S \lesssim 5.62$.
- Combined constraints from the DM relic density, PandaX-II limit, EWBG, EWPO and Higgs searches at colliders places an upper limit on $m_H$, $m_\psi$ and $g_S$.
- GW spectra of viable points are often within reach of future GW experiments.

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