The cS2HDM as a unified framework for dark matter and electroweak baryogenesis

Pedro Gabriel (CFTC-UL/ITP-KIT)

In collaboration with: Thomas Biekötter, M. Margarette Mühlleitner and Rui Santos

Dark Tools workshop

Turin, June 2025

Fundação para a Ciência e a Tecnologia

Funded by FCT in the framework of projects no. CFTC: UIDB/00618/2020 (https://doi.org/10.54499/UIDB/00618/2020), UIDP/00618/2020 (https://doi.org/10.54499/UIDP/00618/2020) and grant no. 2022.11377.BD (https://doi.org/10.54499/2022.11377.BD)

Motivation

The nature of dark matter (DM) and the origin of the baryon asymmetry of the Universe are still two of the biggest mysteries in Physics. The Standard Model (SM), while very successful, fails to explain these two phenomena in a satisfactory way.

Many SM scalar extensions have been studied with the goal of providing an answer to these issues, but most either solve only one of the problems or are under pressure from experimental measurements.

It seems that the minimal framework that allows for DM and electroweak baryogenesis are 2HDM+complex singlet models.

Goal: To put forward a model that provides a suitable pNG DM candidate along with additional sources of CP-violation, while serving as a benchmark for future collider searches.

cS2HDM

The cS2HDM - Scalar sector

$$V = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\phi_1^\dagger\phi_2 + \frac{m_S^2}{2}|\phi_S|^2 - \frac{m_\chi^2}{4}\phi_S^2$$
$$+\frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_2)|\phi_1|^2 + \lambda_7(\phi_1^\dagger\phi_2)|\phi_2|^2$$
$$+\frac{\lambda_8}{2}|\phi_S|^4 + \lambda_9|\phi_1|^2|\phi_S|^2 + \lambda_{10}|\phi_2|^2|\phi_S|^2 + \lambda_{11}(\phi_1^\dagger\phi_2)|\phi_S|^2 + h.c.$$

U(1) soft-breaking term

DM portal couplings

CP-violating terms

Fields

$$\phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{v_1 + \varphi_1 + i\sigma_1}{\sqrt{2}} \end{pmatrix}$$

$$\phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{v_2 + \varphi_2 + i\sigma_2}{\sqrt{2}} \end{pmatrix}$$

$$\phi_S = \frac{v_S + \varphi_S + i\chi}{\sqrt{2}}$$

DM candidate

Mass eigenstates

$$\begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = U(\beta)\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} \qquad \begin{pmatrix} G^0 \\ A_0 \end{pmatrix} = U(\beta)\begin{pmatrix} \sigma_1 \\ \sigma_2 \end{pmatrix} \qquad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \end{pmatrix} = R(\alpha_1, \dots, \alpha_6)\begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_S \\ A_0 \end{pmatrix}$$

Higgs alignment limit

$$\alpha_1 = \beta, \quad \alpha_2 = 0, \quad \alpha_6 = 0 \quad \Rightarrow \quad H_1 = h_{SM}$$

The cS2HDM - Yukawa sector

The most general Yukawa Lagrangian is given by:

$$L_{Yuk} = -\sum_{a=1}^{2}\left((Y_u^a)_{ij}\phi_a Q_i \bar{u}_j + (Y_d^a)_{ij}\tilde{\phi}_a Q_i \bar{d}_j + (Y_l^a)_{ij}\tilde{\phi}_a L_i \bar{e}_j\right) + h.c.$$

To prevent the occurrence of flavor-changing neutral currents (FCNCs), we apply the flavor alignment constrain in which the Yukawa matrices related to each doublet are proportional to each other, meaning they can be diagonalized at the same time

$$Y_u^1 = \xi_u Y_u^2 \qquad Y_d^1 = \xi_d Y_d^2 \qquad Y_l^1 = \xi_l Y_l^2$$

Can be complex; extra source of CP-violation

$$Y_f = \frac{\sqrt{2}m_f}{\xi_f v_1 + v_2}$$

	ξ_u^{Re}	ξ_d^{Re}	ξ_l^{Re}
Type I	0	0	0
Type II	0	∞	∞
LS	0	0	∞
Flipped	0	∞	0

CP violation – Scalar sector

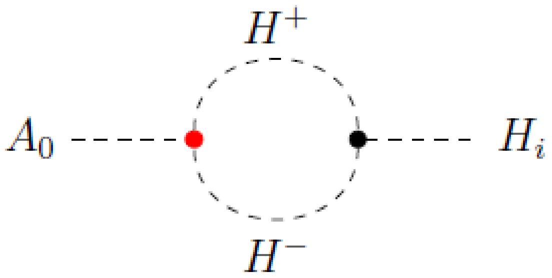
There are two different way of achieving CP-violation in the scalar sector, parameterized by the mixing angles α_4 and α_5 (assuming the alignment limit):

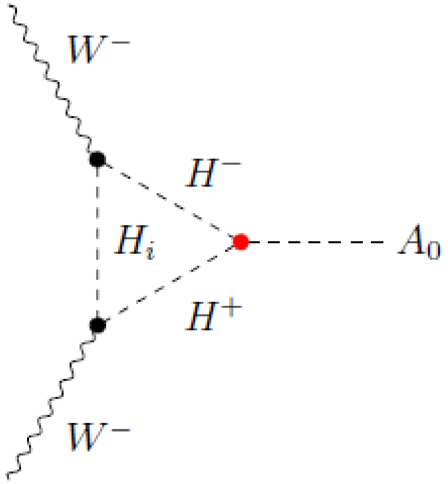
- Explicit mixing between CP-odd and CP-even states when α_4 or α_5 are non-zero.
- CP-violating couplings through λ_5^{Im} and α_3 even when there is no explicit mixing between the CP eigenstates:

$$\alpha_4 = 0, \pi, -\pi \quad \alpha_5 = 0, \pi, -\pi \quad \Rightarrow \quad R_{i4} = R_{4i} = \pm\delta_{i4}$$

$$i\Gamma^{(0)}_{A_0 H_2 H_2} = \frac{c^2_{\alpha_3} v \lambda_5^{Im}}{s_{2\beta}} \qquad i\Gamma^{(0)}_{A_0 H_2 H_3} = \frac{s_{\alpha_3} c_{\alpha_3} v \lambda_5^{Im}}{s_{2\beta}}$$

$$i\Gamma^{(0)}_{A_0 H_3 H_3} = \frac{s^2_{\alpha_3} v \lambda_5^{Im}}{s_{2\beta}} \qquad i\Gamma^{(0)}_{A_0 H^+ H^-} = \frac{v \lambda_5^{Im}}{2 c_\beta s_\beta}$$





CP violation – Yukawa sector

$$i\Gamma^{(0)}_{\mathrm{H_i f\bar{f}}} = \Gamma_{\mathrm{H_i f\bar{f}}} + i\gamma_5 \tilde{\Gamma}_{\mathrm{H_i f\bar{f}}}$$

$$\Gamma_{\mathrm{H_i f\bar{f}}} = \frac{m_f\left[\left(\left|\xi_f\right|^2 c_\beta + \xi_f^{Re} s_\beta\right) R_{i1} + \left(\xi_f^{Re} c_\beta + s_\beta\right) R_{i2} - \xi_f^{Im} R_{i4}\right]}{v\left[\left|\xi_f\right|^2 c_\beta^2 + s_\beta^2 + \xi_f^{Re} s_{2\beta}\right]}$$

$$\tilde{\Gamma}_{\mathrm{H_i f\bar{f}}} = \frac{m_f\left[-\xi_f^{Im} s_\beta R_{i1} + \xi_f^{Im} c_\beta R_{i2} + \left(\left(1-\left|\xi_f\right|^2\right)\frac{s_{2\beta}}{2} + \xi_f^{Im} c_{2\beta}\right) R_{i4}\right]}{v\left[\left(\xi_f^{Im} c_\beta\right)^2 + \left(\xi_f^{Re} c_\beta + s_\beta\right)^2\right]}$$

CP-violation in the Yukawa sector can be achieved in two ways:

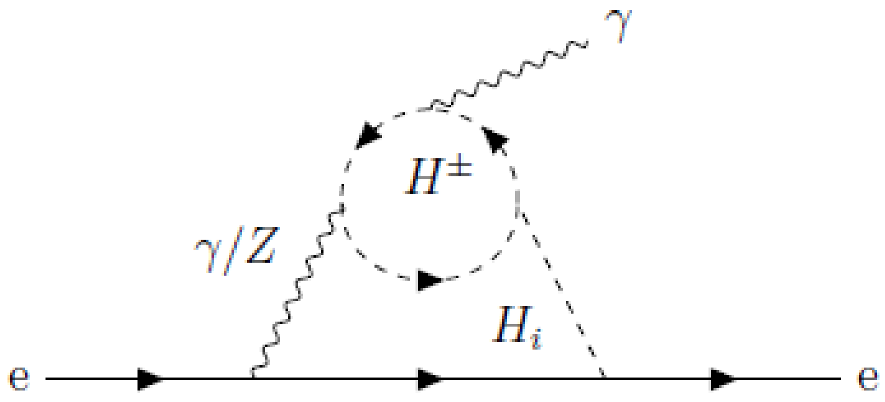
- $R_{i4} \neq 0$, meaning that there must be mixing of the scalar CP eigenstates;
- At least one of the flavor alignment parameters ξ_u, ξ_d and ξ_l must be complex.

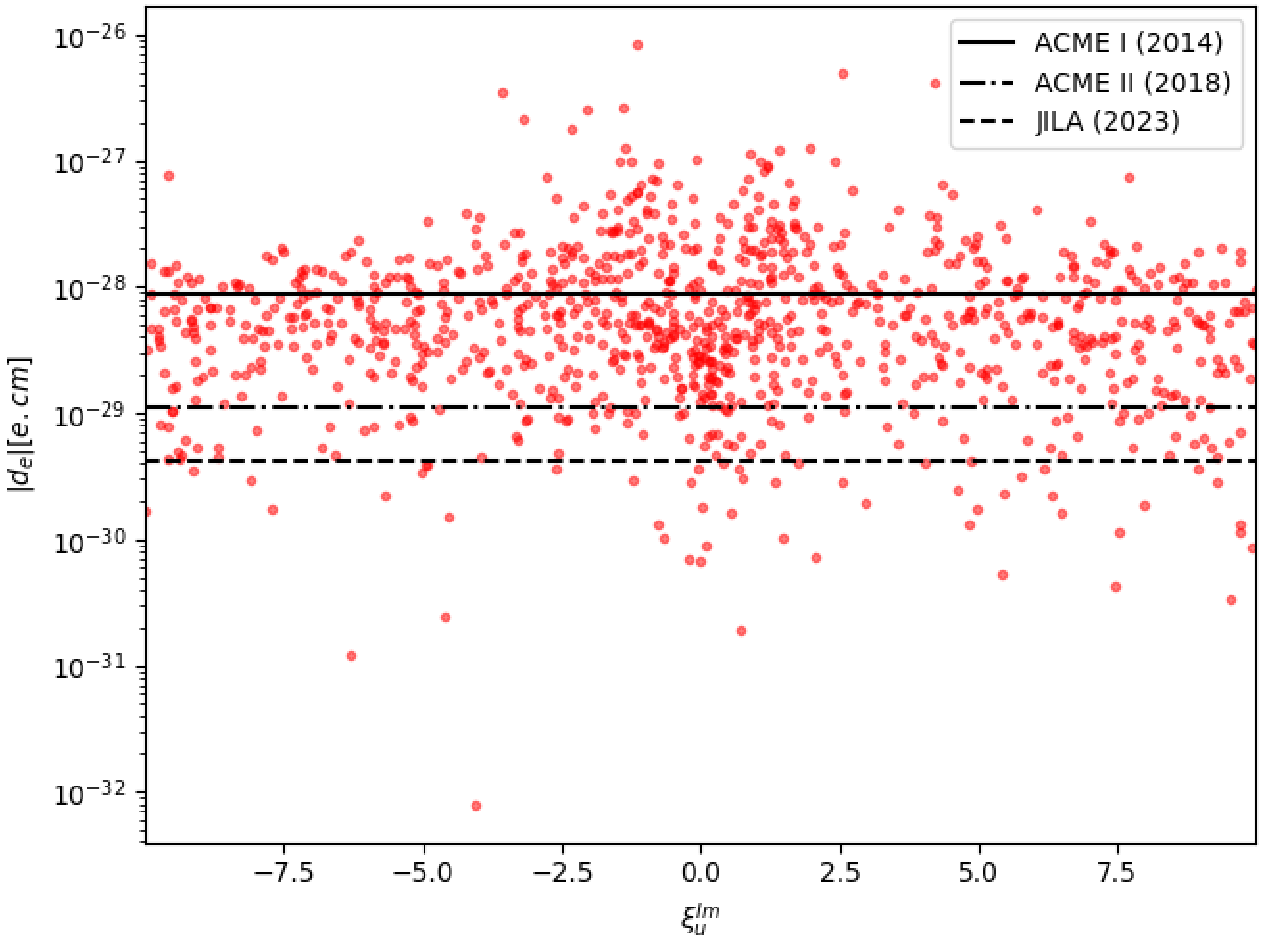
The presence of CP-violation in both the scalar and Yukawa sectors allows for cancellations in the theoretical predictions of the EDMs.

Electric dipole moment (EDM)

$$i d_e \bar{u}(p) \sigma^{\mu\nu} q_\nu \gamma_5 u(p)$$

$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$





Dark sector

$$i\Gamma_{\chi\chi H_i} = v_1\lambda_9 R_{i1} + v_2\lambda_{10} R_{i2} + (v_2 R_{i1} + v_1 R_{i2})\lambda_{11}^{Re} + iv\lambda_{11}^{Im} R_{i4} + v_S\lambda_8 R_{i3}$$

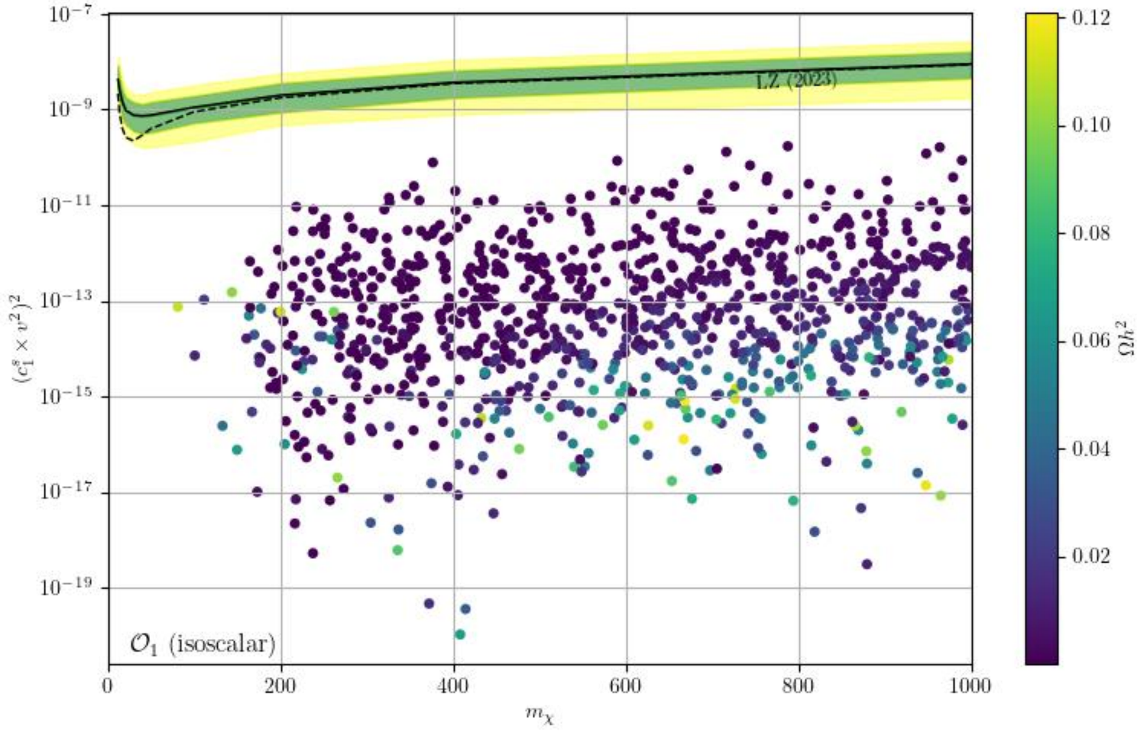
Pseudo-Nambu-Goldstone (pNG) DM candidate that results from the soft-breaking of a U(1) symmetry on the singlet field.

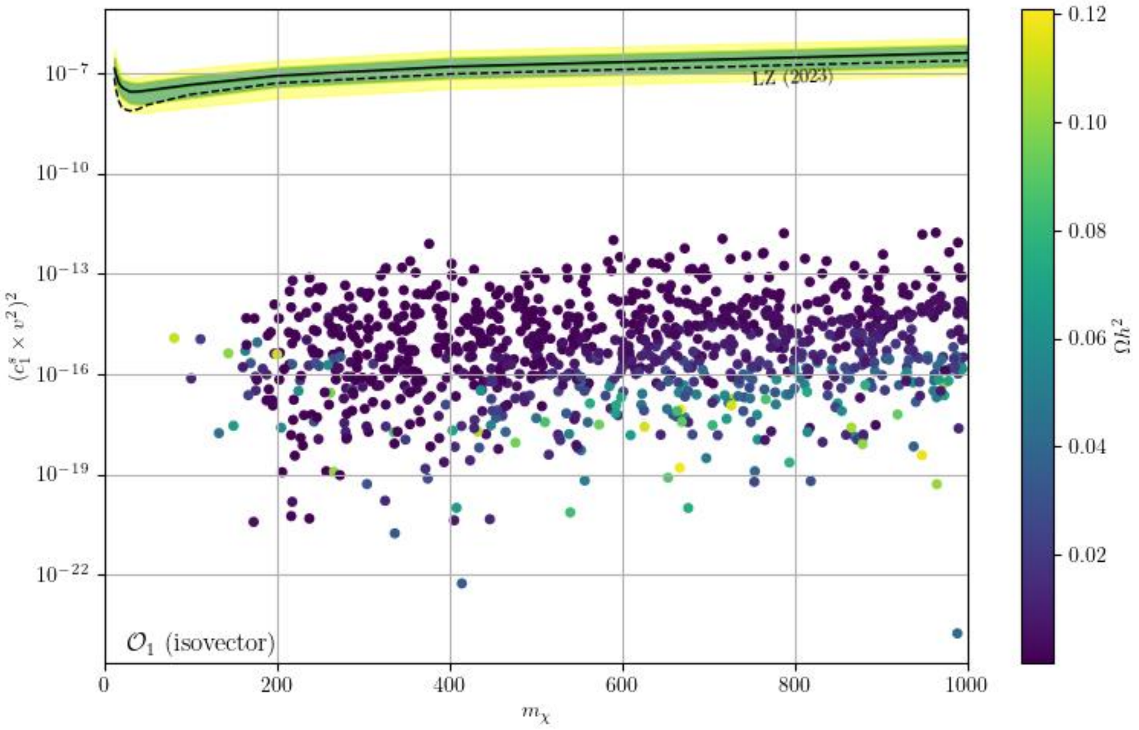
The cS2HDM allows for the DM candidate to couple to the visible sector without the need to go away from the exact alignment limit if α_3, α_4 and/or α_5 are non-zero.

Direct detection

$$\mathcal{L}_{NR} = c_1^N \mathcal{O}_1^N + c_{10}^N \mathcal{O}_{10}^N \qquad \mathcal{O}_1^N = \mathbb{1}_N \qquad \mathcal{O}_{10}^N = -i\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$c_i^s = \frac{c_i^p + c_i^n}{2} \qquad c_i^v = \frac{c_i^p - c_i^n}{2}$$





Conclusions

The cS2HDM is capable of providing a unified framework for both DM and CP-violation.

Contains several sources of CP-violation, both in the scalar sector and the Yukawa sector, which is a requirement for electroweak baryogenesis and to generate EDMs.

Allows for cancellations between the scalar and Yukawa sectors that can lead to suppressed EDMs that are bellow the current experimental limits

Allows for interactions between the dark and visible sectors and CP-violation even in the exact alignment limit ($H_1 = h_{SM}$), given a suitable choice of values for the scalar mixing angles α_3, α_4 and α_5.

Features a pNG DM candidate which has a suppressed scattering cross-section, making it easier to evade the direct detection constraints and probe a larger region of the parameter space at colliders.