



## Dark matter from conformal sectors



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### ABSTRACT

We show that a conformal-invariant dark sector, interacting conformally with the Standard Model (SM) fields through the Higgs portal, provides a viable framework where cold dark matter (CDM) and invisible Higgs decays can be addressed concurrently. Conformal symmetry naturally subsumes the  $\mathbb{Z}_2$  symmetry needed for stability of the CDM. It also guarantees that the weaker the couplings of the dark sector fields to the SM Higgs field, the smaller the masses they acquire through electroweak breaking. The model comfortably satisfies the bounds from Large Hadron Collider (LHC) and Planck Space Telescope (PLANCK 2013).

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### 1. Introduction

As the fundamental scalar discovered at the LHC [1], highly likely to be the Higgs boson of the Standard Model (SM), has been the only new particle discovered so far in searches extending well above a TeV, the emerging picture of the electroweak scale is converging to the SM, within uncertainties in determinations of Higgs boson couplings. However, this SM-only picture, among other vital problems like unnaturalness, suffers from having no candidate particle for cold dark matter (CDM), which is now widely believed to make up the bulk mass of the Universe. If CDM is to be explained by a fundamental particle, then the crystallizing SM-only picture must be supplemented at least by a CDM candidate. Despite the current developments in both direct and indirect detection experiments, and progress in observational cosmology, understanding the particle nature of dark matter (DM), its properties and symmetries, and a model accommodating it, have remained elusive. To begin building a particle physics model for DM, it is important to note that:

- The latest results on cosmological parameters, interpreted in the  $\Lambda$ CDM model, reveal that CDM forms 26.8% of total mass in the Universe [2],

- The latest LHC results on particles beyond the SM, interpreted mainly in supersymmetry (see [3] for a review) and extra dimensions (see [4] for a review) reveal no significant excess in processes with missing energy (plausibly taken away by the CDM particle),
- It is thus conceivable that the CDM particle can be nestled far below the weak scale provided that its couplings to the SM spectrum are sufficiently suppressed.

In view of these properties, in the present work, we build a conservative CDM model by modifying the SM in a minimal way, and observing that:

- A lightweight CDM sector naturally arises if it derives from a conformal-invariant dark sector that couples conformally to the SM particles. The reason is that all the scales in the dark sector, the CDM mass in particular, are directly generated by electroweak breaking, and, in general, the smaller its couplings to the Higgs field, the lighter the CDM particle.
- Conformal symmetry naturally accommodates the  $\mathbb{Z}_2$  symmetry required for longevity of the CDM particle. This feature becomes transparent especially for singlet scalars coupling to the SM Higgs field.

In what follows, we shall construct the CDM model explicitly and analyze it against the latest results from Planck and LHC.

Classical conformal symmetry, entering as an ideal tool into our approach to CDM, plays an important role in various other aspects of the SM and physics beyond it. Basically, conformal symmetry forbids all fixed scales in a theory, and hence, small scales like the

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Higgs mass-squared might be understood by conformal breaking. The stability of Higgs mass against quadratic divergences requires a large fine-tuning at each order of perturbation theory [5], triggering a wide range of beyond the SM extensions. The desire to avoid such unnatural fine tuning has been the major motivation behind numerous beyond-the-SM scenarios. Among them, the conformal symmetry has long been considered as the symmetry principle behind naturalness [6]. It has been shown in [7] that, in a classically conformal symmetric extension of the SM, with a new hidden QCD-like strongly interacting sector, it is possible that all the mass scales both in the SM and in the hidden sector arise through a dynamically generated scale in the hidden sector. In this model, the connection of the hidden sector to the SM is provided by a messenger real singlet scalar, which then triggers spontaneous breaking of the electroweak symmetry of the SM. By the same token, it has been shown in [8] that, although quantum effects break the conformal symmetry explicitly, conformal duality provide a viable renormalization programme for Higgs sector. Attempts at model building in this direction had already noted that, in the post-Higgs era, it is preferable to consider conformal-invariant extensions of the SM. (See also the recent attempt [9] using conformal-invariant interactions with Coleman–Weinberg effective potential, where quadratic and quartic divergences are blinded by dimensional regularization scheme.)

In this Letter, we proceed based on the hypothesis that conformal symmetry automatically induces the required  $\mathbb{Z}_2$  symmetry for stabilizing the CDM, and that at the classical level, it is essential for the existence of small mass scales in nature. We thus consider a generic, conformally-invariant DS involving scalars, gauge fields and fermions in addition to the SM particle spectrum. Each of these fields can be a CDM candidate depending on the symmetries of the DS. These features ensure that a conformal-invariant DS can yield a simple and transparent model of CDM. Imposing conformal symmetry on DS provides a naturally light, weakly interacting dark sector. The mass-squared of the SM Higgs field, the only parameter that breaks conformal symmetry explicitly, generates all the particle masses in the SM and DS. The CDM candidate(s) acquire mass only from its coupling through the Higgs portal, and the smaller the coupling of the DM to Higgs, the smaller its mass compared to electroweak scale. Conformal invariance enhances the predictive power of the model, and numerical analysis shows that conformal coupling of DS to Higgs field is the decisive parameter. We study the mass spectrum of the DS, and outline regions of parameter space which satisfy constraints from the LHC searches on the invisible width of the Higgs boson, and from Planck Space Telescope observations on the relic density of the CDM content.

## 2. A conformal model for dark matter

A CDM candidate which belongs to a dark sector (DS) and is composed of SM singlets, can couple to the SM fields via Higgs, hypercharge or neutrino portals. These interactions, invariant under both SM and DS gauge symmetries, already exist at the renormalizable level, and exhibit conformal invariance if CDM particles are charged under a dark gauge symmetry. Even when the DS is not governed by a gauge symmetry, as mentioned above, longevity of the CDM particle necessitates at least a  $\mathbb{Z}_2$  symmetry. It is thus conceivable to consider a conformally-invariant DS which couples conformally to the SM fields. This conformal setup has the advantage that a  $\mathbb{Z}_2$  symmetry is inherently incorporated.

Motivated by the discovery of the Higgs boson, which exhibits all the properties appropriate for an SM-like Higgs, and the wealth of experimental information supporting the SM, we adopt the SM as is, and impose that only the dark matter candidate obeys conformal invariance. Previous authors have investigated cases in

which both the dark matter scalar and the Higgs boson are conformally invariant [10]. However, our aim here is to show that a minimally modified SM by the addition of a conformal dark matter candidate can satisfy bounds from both dark matter and invisible Higgs width. This scenario does not solve the fine-tuning problem for the additional scalar particle, though one can rely on alternative solutions, such as additional symmetries or particles to resolve it. For instance, in [11] the fine-tuning problem of singlet scalar is resolved by adding  $SU(2)$  singlet or doublet vector fermions such that the mass-squared value of the singlet scalar is protected against quantum corrections.

The main ingredient of our model is a conformally-invariant scalar field that couples conformally to the SM Higgs doublet. The scalar field, an SM-singlet belonging to the DS, can be a real scalar  $S$ , or a complex scalar  $\phi$ , charged under a dark gauge group  $U(1)_D$ . This group contains a gauge boson  $A'_\mu$ , and, in addition, the DS sector can include a dark fermion  $\psi$  charged under  $U(1)_D$ .<sup>1</sup> Below, we investigate these fields one by one.

### 2.1. Dark real scalar

The Higgs doublet  $H$  and real singlet  $S$  interact via

$$\mathcal{L}_S = (D_\mu H)^\dagger D^\mu H + \frac{1}{2} \partial_\mu S \partial^\mu S - V_S, \quad (1)$$

where the conformal-invariant potential energy

$$V_S = \frac{m_H^2}{2} H^\dagger H + \frac{\lambda_H}{4} (H^\dagger H)^2 + \frac{\lambda_S}{4} S^4 - \frac{\lambda}{4} H^\dagger H S^2, \quad (2)$$

involves no interaction with scaling dimension different than 4 ( $S$ ,  $S^2$ ,  $S^3$ ,  $S^5$  and so on), thus giving rise to automatically  $\mathbb{Z}_2$ -symmetric interactions for  $S$ . The only exception is  $H$ ; its mass parameter  $m_H^2$  generates all the scales in the DS, and in the SM upon electroweak breaking. With  $\lambda_H > 0$  and  $\lambda_S > 0$ , the potential is bounded from below, and its minimization yields a phenomenologically interesting scenario where, for  $m_H^2 < 0$ , there is a local maximum at  $\langle 0|H|0\rangle \equiv v_H = 0$ ,  $\langle 0|S|0\rangle \equiv v_S = 0$ , and a minimum at

$$v_H^2 = -\frac{m_H^2}{\lambda_H}, \quad v_S^2 = 0. \quad (3)$$

For excitations of  $H$  above the vacuum

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} H_3 + iH_4 \\ \sqrt{2}v_H + H_1 + iH_2 \end{pmatrix}, \quad (4)$$

we obtain a diagonal mass matrix for  $H_1$  and  $S$  (the massless  $H_{2,3,4}$  are Goldstone bosons eaten by  $W^\pm$  and  $Z$ ). Here  $H_1 \equiv h$  is the SM Higgs boson (with the additional interaction  $\frac{\lambda}{4} H^\dagger H S^2$  in Eq. (2) above). After electroweak breaking  $S$  acquires mass, and conformal symmetry gets broken to  $\mathbb{Z}_2$  parity. The mass-squared of  $S$  is proportional to  $\lambda$  so that, as anticipated before, the smaller the  $|\lambda|$ , the lighter the real singlet scalar  $S$ . The model thus accommodates a naturally light, weakly interacting, stable scalar sector which can set a standard for studies on light singlet scalar fields [12]. The masses of the scalar fields

$$m_h^2 = \lambda_H v_H^2, \quad m_S^2 = -\frac{\lambda}{2} v_H^2, \quad (5)$$

exhibit the hierarchy,  $m_h^2 \gg m_S^2$ , if  $|\lambda|$  is small enough.

<sup>1</sup> Higher-rank gauge groups do not bring any further insight so we shall contend ourselves with a simple  $U(1)_D$  symmetry.

## 2.2. Dark complex scalar

For the complex scalar  $\phi$ , interactions with Higgs field are encoded in

$$\mathcal{L}_\phi = (D_\mu H)^\dagger D^\mu H + \partial_\mu \phi^* \partial^\mu \phi - V_\phi, \quad (6)$$

where the conformal-invariant potential

$$V_\phi = \frac{m_H^2}{2} H^\dagger H + \frac{\lambda_H}{4} (H^\dagger H)^2 + \frac{\lambda_\phi}{4} (\phi^* \phi)^2 - \frac{\lambda}{4} H^\dagger H \phi^* \phi, \quad (7)$$

has the same structure as the potential in Eq. (2). Thanks to conformal symmetry, it retains a  $\mathbb{Z}_2$  symmetry associated with  $\phi$ . The potential is bounded from below for  $\lambda_H > 0$  and  $\lambda_\phi > 0$ , and possesses a phenomenologically interesting minimum at

$$v_H^2 = \frac{4\lambda_\phi m_H^2}{\lambda^2 - 4\lambda_H \lambda_\phi}, \quad v_\phi^2 = \frac{2\lambda m_H^2}{\lambda^2 - 4\lambda_H \lambda_\phi}. \quad (8)$$

Parametrizing  $H$  as in (4) and the complex scalar as  $\phi = \frac{1}{\sqrt{2}} \times (\sqrt{2}v_\phi + \phi_1 + i\phi_2)$ , the  $H_1$  and  $\phi_1$  mix with through mass matrix

$$M_{H_1, \phi_1}^2 = \begin{pmatrix} \lambda_H v_H^2 & -\frac{\lambda}{2} v_H v_\phi \\ -\frac{\lambda}{2} v_H v_\phi & \lambda_\phi v_\phi^2 \end{pmatrix}, \quad (9)$$

where now the Goldstone sector involves also  $\phi_2$ . After diagonalization, this mass matrix yields the physical scalars  $h$  and  $\varphi$  with masses

$$m_{h, \varphi}^2 = \frac{1}{4} (2\lambda_H + \lambda) v_H^2 \left( 1 \pm \sqrt{1 + \frac{2\lambda(\lambda^2 - 4\lambda_H \lambda_\phi)}{\lambda_\phi(2\lambda_H + \lambda)^2}} \right), \quad (10)$$

and mixing angle

$$\tan^2 2\theta = \frac{\lambda^3}{2\lambda_\phi(2\lambda_H - \lambda)^2}. \quad (11)$$

The complex field  $\phi$  behaves differently than the real scalar  $S$ . The mass of  $\varphi$  breaks conformal symmetry, the VEV of  $\phi$  breaks  $\mathbb{Z}_2$  parity, and hence,  $\varphi$  cannot be a CDM candidate. A viable CDM candidate is found either in the gauge boson of gauge  $U(1)_D$  or in a dark fermion sterile under SM but charged under  $U(1)_D$ , which can be added to the spectrum. These candidates are analyzed below. The singlet scalars as a solution to fine-tuning problem have been discussed in [13]. It has been shown in [9] that, with no extra global or local symmetry introduced, the imaginary component of the complex singlet scalar  $\phi_2$  is also a viable DM candidate, and that its stability is automatically protected by CP invariance.

## 2.3. Vacuum stability conditions

The tree-level potential minimum is simply guaranteed by requiring

$$\lambda^2 - 4\lambda_H \lambda_\phi > 0, \quad (12)$$

while the requirement that the potential is bounded from below is:

$$\lambda_H > 0 \quad \text{and} \quad \lambda_\phi > 0. \quad (13)$$

A full two-loop analysis of the vacuum stability conditions would lead to a precise statement of perturbativity for the quartic couplings and a more restricted range of parameter space, but this is beyond the scope of this work. We rely on previous analyses [14], which considered two possible criteria to constrain the values of the couplings at the cut-off scale, thus leading to a perturbative loop expansion of the potential. The first option is to take the SM

two-loop result and apply it to each of the quartic couplings at the cut-off scale individually. The second, less restrictive, is to follow the constraints of [15]

$$\lambda_H < 8\pi/3, \quad \lambda_S < 2\pi/3, \quad \lambda < 8\pi \quad \text{for real singlet,}$$

$$\lambda_H < 8\pi/3, \quad \lambda_\phi < 8\pi/3, \quad \lambda < 16\pi \quad \text{for complex singlet,}$$

where the perturbativity condition  $\lambda'_i < 4\pi$  is used. We choose this scenario, as the constraints are cut-off independent. In Section 3, we shall see that these conditions are comfortably satisfied by our parameters in the region of phenomenological interest, as all the couplings in our model are potentially less than 0.1 to satisfy the relic density bounds.

## 2.4. Dark gauge boson

Gauged  $U(1)_D$  modifies the original Lagrangian (6) by contributions to the kinetic term via  $\partial_\mu \phi \rightarrow D_\mu \phi = (\partial_\mu - ie_D A'_\mu) \phi$ , where  $e_D$  is the  $U(1)_D$  gauge coupling. The Lagrangian

$$\mathcal{L}_{A'} = \mathcal{L}_\phi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} \quad (14)$$

where  $\mathcal{L}_\phi$  is the complex scalar Lagrangian from Eq. (6). The  $A'_\mu$  acquires the mass

$$m_{A'}^2 = \frac{\lambda}{\lambda_\phi} e_D^2 v_H^2, \quad (15)$$

from  $U(1)_D$  breaking. Possible kinetic mixing between  $U(1)_D$  and hypercharge  $U(1)$  are avoided by imposing  $A'_\mu \rightarrow -A'_\mu$  and  $\phi \rightarrow \phi^*$  invariance [16]. The gauged vector CDM models have been studied in [16,17].

## 2.5. Dark fermion

Just like the scalars  $S$  or  $\phi$ , there can exist a dark fermion  $\psi$  in DS. It can be the CDM by itself or in addition to the  $A'_\mu$  and the real scalars  $S$ . As a sterile fermion charged under  $U(1)_D$ , it can interact only with  $\phi$

$$\mathcal{L}_\psi = \bar{\psi} i \not{\partial} \psi + \frac{\lambda_\psi}{2} \phi \bar{\psi}^c \psi, \quad (16)$$

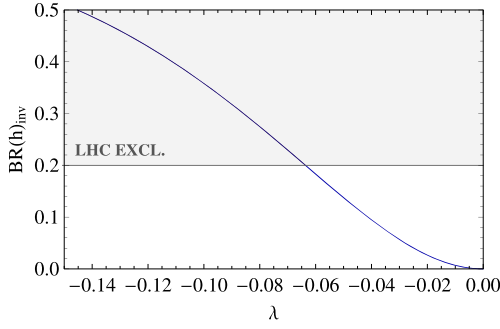
where  $\psi^c$  is charge-conjugate of  $\psi$ , and  $U(1)_D$  charges satisfy  $Q_\phi = 2Q_\psi$ . Upon  $U(1)_D$  breaking, the dark fermion acquires the mass

$$m_\psi^2 = \lambda_\psi v_\phi^2 = \frac{\lambda_\psi \lambda}{2\lambda_\phi} v_H^2, \quad (17)$$

which is proportional to  $\lambda$ . This fermion accesses the SM fields via  $h$ - $\varphi$  mixing. (See [18] for a similar models with sterile neutrinos.)

## 3. Phenomenological implications

The DS fields studied above can have important impact on collider experiments and astrophysical observations. While a detailed analysis can shed more light on the model parameters, we here focus exclusively on the Higgs invisible rate measured at the LHC and the current CDM density reported by PLANCK 2013, and show that the experimental data can be satisfied within each scenario, and for a minimal number of parameters.



**Fig. 1.**  $BR_h^{\text{inv}}$  for  $X = S$  (blue) with LHC exclusion region (in light grey). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

### 3.1. Bounds from Higgs invisible width

If kinematically allowed, the Higgs can decay into the dark matter candidates. Then the decay  $h \rightarrow XX$ ,  $X = S, \varphi, \psi, A'_\mu$  constitute the Higgs invisible rate  $\Gamma_{\text{inv}}$ , and is constrained by measurements of the Higgs width. For a given  $X$  the width is given by

$$\Gamma_{h \rightarrow XX} = \frac{|\mathcal{M}(X)|^2}{32\pi m_X} \sqrt{1 - 4 \frac{m_X^2}{m_h^2}}, \quad (18)$$

where the matrix elements for real scalars, vector bosons and complex scalars are, respectively,

$$\begin{aligned} |\mathcal{M}(S)|^2 &= \frac{\lambda^2}{8} v_H^2, & |\mathcal{M}(\psi)|^2 &= \frac{\lambda_\psi^2}{4} \sin^2 \theta m_h^2, \\ |\mathcal{M}(A')|^2 &= \frac{\lambda v_H^2 e_D^4 \sin^2 \theta}{4 \lambda_\phi m_{A'}^4} (12m_{A'}^4 - 4m_{A'}^2 m_h^2 + m_h^4), \\ |\mathcal{M}(\phi)|^2 &= \left| \frac{3v_H \sin 2\theta}{4\sqrt{2}} \left( \lambda_H \sin \theta - \sqrt{\frac{\lambda \lambda_\phi}{2}} \cos \theta \right) \right. \\ &\quad \left. - \frac{\lambda v_H}{4\sqrt{2}} f(\theta) + \sqrt{\frac{\lambda}{2\lambda_\phi}} g(\theta) \right|^2. \end{aligned} \quad (19)$$

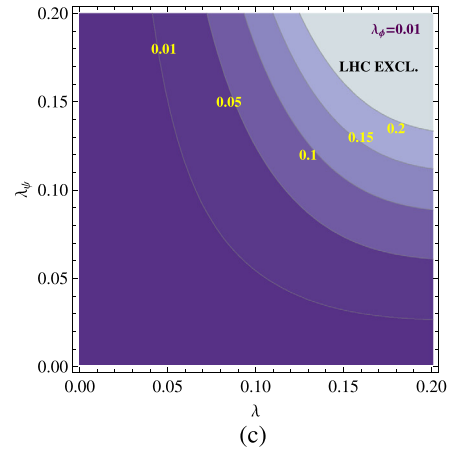
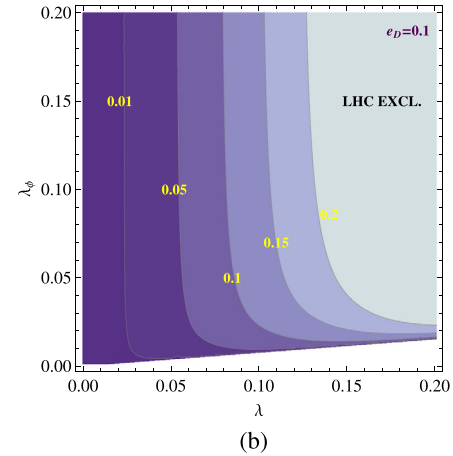
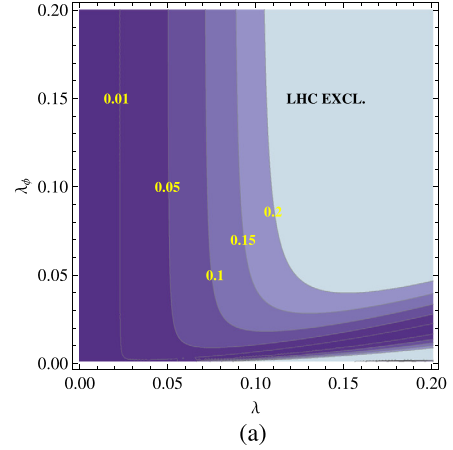
Here  $f(\theta) = \cos^3 \theta - \sin 2\theta \sin \theta$  and  $g(\theta) = \sin^3 \theta - \sin 2\theta \cos \theta$ . For  $m_h = 126$  GeV,  $\Gamma_h^{\text{vis}} = 4.21$  MeV [20], and Higgs invisible branching  $BR_h^{\text{inv}} = \Gamma_h^{\text{inv}} / (\Gamma_h^{\text{inv}} + \Gamma_h^{\text{vis}})$  is constrained to be less than 19% at  $2\sigma$  [19].

If DS involves just  $S$ ,  $\Gamma_h^{\text{inv}} = \Gamma_{h \rightarrow SS}$ , and the invisible width depends only  $\lambda$ . In Fig. 1 we plot the bound on  $\lambda$  from  $BR_h^{\text{inv}}$ . The LHC-allowed region (represented by the white part of the plot) corresponds to  $\lambda \gtrsim -0.063$  (yielding  $m_S \lesssim 30$  GeV for the DM real scalar).

If DS consists of the complex scalar  $\phi$  then  $\Gamma_h^{\text{inv}}$  can be either  $\Gamma_{h \rightarrow \varphi\varphi}$  or  $\Gamma_{h \rightarrow A'A'}$  or  $\Gamma_{h \rightarrow \psi\psi}$ . They each are plotted in Fig. 2 for different  $BR_h^{\text{inv}}$  values. In general, LHC-excluded regions occur at larger values of couplings, and are depend on other couplings. For instance, if  $e_D$  is increased, the light grey region moves to upper right corner with  $\lambda$  and  $\lambda_\phi$  getting closer to  $e_D$  ( $\lambda_\phi \gtrsim 0.17$ ,  $\lambda \gtrsim 0.2$ ).

### 3.2. Bounds from relic density

The relic density of CDM today is determined by rate at which the DM coannihilate into SM states ( $XX \rightarrow \text{SM}$ ). The rate is dominated by  $s$ -channel annihilation through mediator  $X = h$  or  $\varphi$  using a Breit-Wigner propagator



**Fig. 2.** Contour plots of  $BR_h^{\text{inv}}$  for  $X = \varphi$  (top),  $X = A'_\mu$  (middle), and  $X = \psi$  (bottom) with LHC exclusions (light-blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

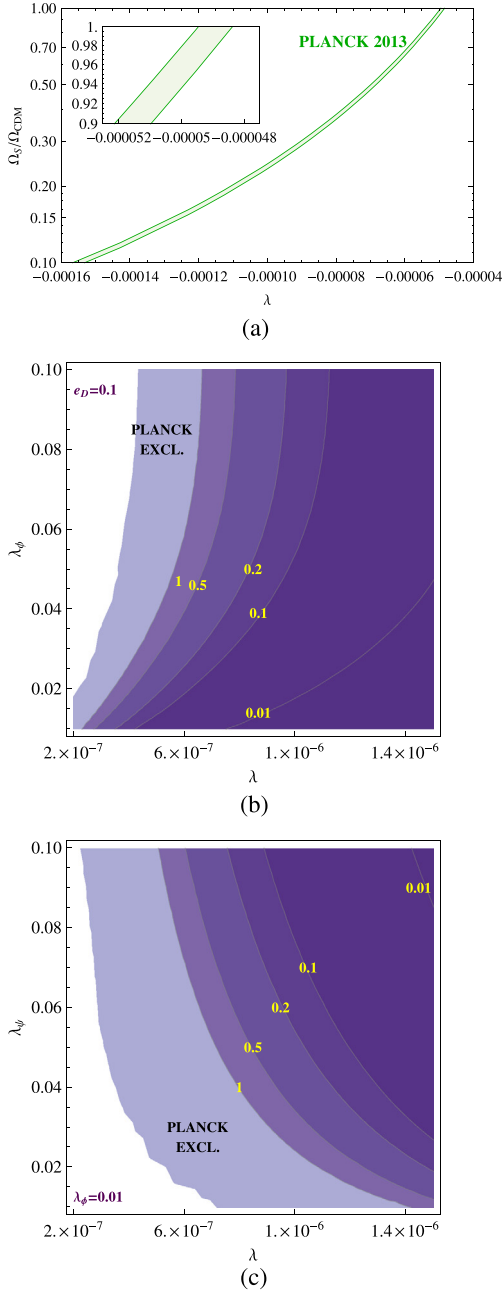
$$D_X(s) = \frac{1}{s - m_X^2 + im_X \Gamma_X^{\text{tot}}}, \quad (20)$$

where  $\Gamma_X^{\text{tot}}$  is the total width (visible plus invisible) of  $X$ .

For  $X = S$ , the relic density

$$\langle \sigma v_{\text{rel}} \rangle = \frac{\lambda^2 v_H^2}{4\sqrt{s}} |D_h(s)|^2 \Gamma_h^{\text{vis}}(\sqrt{s}), \quad (21)$$

is enhanced near the Higgs resonance,  $\sqrt{s} \approx m_h$  at which  $\Gamma_h^{\text{vis}}(\sqrt{s})$  becomes the visible width of the Higgs boson [20]. In the left panel of Fig. 3 we depict the ratio  $\Omega_S / \Omega_{\text{CDM}}$ , where  $\Omega_S$  is the



**Fig. 3.** Relic abundance plots of the CDM candidates  $S$  (top),  $A'_\mu$  (middle) and  $\psi$  (bottom). Contours indicate the ratio  $\Omega_X/\Omega_{\text{CDM}}$ .

relic density of  $S$ , as a function of  $\lambda$ . The 2013 PLANCK measurement of the relic density is  $\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$  at 68% CL [21], and is represented in the figure by the thin green strip. The figure shows that a single real scalar singlet is able to saturate entire CDM density if  $-4.8 \times 10^{-5} \gtrsim \lambda \gtrsim -4.9 \times 10^{-5}$  (or  $0.73 \text{ GeV} \lesssim m_S \lesssim 0.75 \text{ GeV}$ ). This narrow region is consistent with  $\lambda \gtrsim -0.063$  determined from Fig. 1.

In the case of the SM particle content being augmented by a complex scalar  $\phi$ , the dark gauge boson  $A'_\mu$  and/or the dark fermion  $\psi$  can serve as CDM particles. The relic density of  $A'_\mu$ , diluting through  $A'_\mu A'_\mu \rightarrow \text{SM}$  annihilation, is given by

$$\langle \sigma v_{\text{rel}} \rangle = \frac{e_D^4 \lambda v_H^2}{2\lambda_\phi \sqrt{s} m_{A'}^4} |D(s)|^2 (12m_{A'}^4 - 4m_{A'}^2 s + s^2), \quad (22)$$

through  $h$  and  $\varphi$  mediators encoded in the propagator

$$D(s) = D_h(s) \sin \theta \sqrt{\frac{\Gamma_h(s) \Gamma_h^{\text{vis}}}{\Gamma_h(m_h)}} - D_\varphi(s) \cos \theta \sqrt{\frac{\Gamma_\varphi(s) \Gamma_\varphi^{\text{vis}}}{\Gamma_\varphi(m_\varphi)}}.$$

Here  $\Gamma_h$  is the Higgs fermionic width

$$\Gamma_h(s) = \frac{N_c^f m_f^2 \sqrt{s}}{16\pi v_H^2} \left(1 - 4 \frac{m_f^2}{s}\right)^{3/2} \cos^2 \theta,$$

and  $\Gamma_\varphi(s) = \Gamma_h(s) (\cos \theta \rightarrow \sin \theta)$  is the  $\varphi$  width. The relic density of  $A'_\mu$  is enhanced at  $\sqrt{s} = m_\varphi$ , and almost independent of  $e_D$ . The ratio  $\Omega_{A'}/\Omega_{\text{CDM}}$  is plotted in the middle panel of Fig. 3 for  $e_D = 0.1$ . This plot is consistent with Fig. 1. Clearly,  $A'_\mu$ , now a viable CDM candidate, can saturate the CDM in the Universe either all by itself, or partially.

The relic density of the dark fermion

$$\langle \sigma v_{\text{rel}} \rangle = \frac{\lambda_\psi^2 \sqrt{s}}{2} |D(s)|^2 \quad (23)$$

is also pronounced at  $\sqrt{s} \sim m_\varphi$ . From the right panel of Fig. 3, where we plot the relic density due to the dark fermion only, it is clear that this fermion is a viable CDM candidate. The panels of this figure, separately or together, can account for the abundance of CDM in the Universe for wide ranges of parameters.

### 3.3. Dark matter searches and astrophysical constraints

Our model predicts candidates for dark matter of low mass, which have, up to now, shown resilience to experimental constraints. Indirect constraints come from the Cosmic Microwave Background, gamma rays and neutrino experiments in particular. Several observations of cosmic and gamma-ray fluxes have been linked to the possible signals of annihilation or decays of DM particles. The 511 keV line emission from the Galaxy detected by the SPI spectrometer on the INTEGRAL satellite [22], the excesses of microwaves and gamma rays in the inner Galaxy revealed by the WMAP and Fermi satellites [23], the evidence for a 130 GeV spectral line in the Fermi data [24], which predicts that DM particles with masses below 10 GeV have the annihilation cross section at  $\sigma_{\text{th}} v \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$ , or the rise in the positron fraction above 10 GeV observed by PAMELA [25] and AMS-02 [26], which even though it could be interpreted as the signal from nearby pulsars or astrophysical objects [27], it still provides stringent bounds on the DM annihilation cross section to electron–positron or muon–antimuon pairs [28], and the current constraint on dark matter scattering with nuclei largely through spin-dependent couplings from the IceCube experiment [29], all have been interpreted as physics associated with DM [30]. Currently a dark matter interpretation for these signals is far from clear, given limited statistics (for the Fermi line) or large systematics or astrophysical backgrounds (for the positron, and the 511 keV emission), as shown in an up-to-date review of indirect searches, see [31].

In direct searches, various anomalies have remained, while new constraints have continued to close the allowed parameter space for an elastically scattering light DM particle in the 7–12 GeV mass region that can explain the signals.

These anomalies have become the target for searches of light DM, and the null results from XENON10 [32], XENON100 [33], PICASSO [34], COUPP [35], CDMS-Ge low energy [36] and CDMSlite [37] constrained the region. The strongest constraints are obtained from XENON in the spin-independent case, but they are subject to nuclear recoil energy calibration uncertainties near the threshold [33].

CDMS-Si [38] reported an excess of three events at threshold consistent with a light DM candidate. The preferred region appears consistent with the excess observed by CoGeNT [39], though may be in conflict with the XENON100 constraint.<sup>2</sup>

Most recently, LUX has published data on light DM with a low nuclear recoil energy threshold of 3 keV [42]. For the three CDMS events, assuming equal DM coupling to the proton and neutron, and spin-independent scattering, at a cross-section  $2 \times 10^{-41} \text{ cm}^2$ , LUX would be expected to see approximately 1500 events. Thus LUX is able to put a strong constraint on the entire preferred region of the CDMS-Si three events.

The results from LUX rule out the region where all three experiments overlap. PICASSO, XENON10 and CDMS-Ge low-energy are also competitive in this range, and various dark matter models offer alternative assumptions to weaken the LUX constraint relative to the CDMS-Si and CoGeNT regions of interest. However, when corrected for energy nuclear recoil energy calibration, LUX provides the strongest bounds on dark matter masses above 5.5 GeV. Neither LUX or XENON100 are sensitive below this threshold [43], and our results still stand.

In addition, observations at Bullet Cluster [44] could be used to place a constraint on the quartic DM coupling  $\lambda_S$ , as the ratio DM scattering cross section over the mass must be less than  $1.25 \text{ cm}^2/\text{g}$ , would imply a lower bound on the mass of the dark matter candidate,  $m_{\text{DM}} > 64 \text{ MeV}$  [45], consistent with what we have obtained here. See also [46] and references therein for a comprehensive review on direct and indirect DM searches.

#### 4. Conclusion

In this work, we constructed a CDM model by augmenting the SM particle content by a conformal-invariant dark sector, interacting conformally with the SM through the Higgs portal, and including either a singlet real, or a complex scalar field. While the real singlet does not develop a VEV and can become itself a DM candidate, the complex scalar scenario has to be augmented by a dark sector containing a vector gauge boson, or a fermion charged under an additional symmetry  $U(1)_D$ . The near conformal invariance of the SM, with initially massless fermions and gauge bosons, supports the idea that, in beyond the SM scenarios, additional sectors should also respect the conformal symmetry. The only term which breaks the conformal symmetry is the squared mass of the Higgs, which after electroweak symmetry breaking, is responsible for the scales for both the SM and DS. Our main motivation for introducing conformal invariance is that it naturally embodies a  $\mathbb{Z}_2$  symmetry, which is crucial for stability of DM. As a result of conformal invariance, the lighter the dark sector fields, the weaker their couplings to Higgs boson, and this implies that dark matter and invisible Higgs decays are closely related phenomena, and that conformal invariance provides a natural framework that connects them. We have shown that either the scalar singlet, or the gauge boson and fermion, alone or in combination, respect constraints on the invisible width of the Higgs boson, as inferred at LHC, and comfortably satisfy measurements from PLANCK 2013 on relic density, while being consistent with the constraints from dark matter searches. Thus the model presented here provides viable scenario for cold dark matter. Though additional particles and interactions would need to be added to resolve some other outstanding issues in the SM, such as the hierarchy problem, the strength of the model lies in its simplicity and minimal number of param-

eters, thus predictability. This model can be an integral part of the Project X efforts [47].

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