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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).

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 ΛCDM 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 form 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 ϕ, charged under a dark gauge group $U(1)_D$. This group contains a gauge boson A'_μ, and, in addition, the DS sector can include a dark fermion ψ charged under $U(1)_D$.[1] Below, we investigate these fields one by one.

2.1. Dark real scalar

The Higgs doublet H and real singlet S interact via

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

where the conformal-invariant potential energy

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

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 $\langle 0|H|0\rangle \equiv \upsilon_H = 0$, $\langle 0|S|0\rangle \equiv \upsilon_S = 0$, and a minimum at

$$\upsilon_H^2 = -\frac{m_H^2}{\lambda_H}, \qquad \upsilon_S^2 = 0. \tag{3}$$

For excitations of H above the vacuum

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} H_3 + iH_4 \\ \sqrt{2}\upsilon_H + H_1 + iH_2 \end{pmatrix}, \tag{4}$$

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 λ 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

$$m_h^2 = \lambda_H \upsilon_H^2, \qquad m_S^2 = -\frac{\lambda}{2}\upsilon_H^2, \tag{5}$$

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

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