Higgs Naturalness and Dark Matter Stability by Scale Invariance

Jun Guo$^{1,}$ and Zhaofeng Kang$^2,\dagger$

$^1$State Key Laboratory of Theoretical Physics and Kavli Institute for Theoretical Physics China (KITPC), Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China
$^2$Center for High-Energy Physics, Peking University, Beijing, 100871, P. R. China

(Dated: April 1, 2014)

Extending the spacetime symmetries of standard model (SM) by scale invariance (SI) may address the Higgs naturalness problem. In this letter we embed dark matter (DM) into this framework. The DM model can be pinned down, two-Higgs-doublet plus a real singlet, if: (I) the symmetry protecting DM stability is accidental due to the model structure rather than artificial; (II) the light SM-like Higgs boson is the pseudo Goldstone boson of SI anomaly. The extra Higgs doublet triggers electroweak symmetry breaking via the Coleman-Weinberg mechanism and moreover controls DM dynamics. DM mass originates from EWSB, and should be around 1 GeV owing to bounds from Higgs invisible decay, pointing to the GoGenT anomaly. The model can be tested soon both from DM experiments and LHC searches for heavy Higgs states around 370 GeV.

PACS numbers:

Scale invariance (SI) “removes” quadratic divergency (QD) Recently, the LHC discovered a new resonance, which is putative the Higgs boson predicted by the SM [1]. Its couplings are well consistent with the SM predictions and give no illustrative hints for new physics beyond the SM. However, this by no means implies the end of SM. We have a variety of reasons to go beyond the SM, e.g., its lack of DM candidates. The most robust one is theoretical: If the Higgs boson is fundamental, it will suffer QD which renders the weak scale instable under quantum corrections. Removing QD guides the direction of new physics in decades.

A new symmetry may be indispensable to protect this particle, e.g., the well known supersymmetry. In 1995, classical SI was proposed by Bardeen as a candidate [2]. Here we present the argument. QD may be exaggerated by the choice of an improper regularization method like the cut-off regularization. While in the more elaborate dimension regularization (DR) [3] it is not worse than the logarithmic divergency (QD) in the SM sector, thus facing the QD problem again. But SI still insist on the right to use cut-off regularization for the logarithmic divergency (QD) which contains a single classical field $\phi_{cl}$. In the scales theory, at one-loop level $V_{\text{eff}}(\phi_{cl})$ can be generically written as

$$V_{\text{eff}} = A\phi_{cl}^4 + B\phi_{cl}^4 \ln \frac{\phi_{cl}^2}{Q^2},$$

(1)

with $Q$ the renormalization scale. $A$ and $B$ are functions of dimensionless constants involving the couplings of $\phi_{cl}$. In the NMS scheme, they are given by

$$A = \frac{\lambda}{8} + \frac{1}{64\pi^2} \sum_P n_P g_P^4 \left( -A_P + \ln g_P^2 \right),$$

$$B = \frac{1}{64\pi^2} \sum_P n_P g_P^4,$$

(2)

with $\lambda$ the tree-level quartic coupling constant in the potential. $P$ sums over particles which have internal degrees of freedom $n_P$ and field-dependent masses $m_P = g_P \Phi_{cl}$. The factor $A_P = 3/2, 3/2, 5/6$ for the spin 0, 1/2 and 1 particles, respectively. Due to the field-dependent logarithmic term, an extreme is created given $\ln(Q/\langle \phi_{cl} \rangle) = 1 + A/2B$. To avoid a large logarithmic term such that the loop-expansion of $V_{\text{eff}}$ is invalid, one may want to choose $Q = \langle \phi_{cl} \rangle$ and then $A/B|_{Q=\langle \phi_{cl} \rangle} = -1/2$. Expanding around $\langle \phi_{cl} \rangle$, it is not difficulty to get the cur-

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$^1$ Here argument of SI getting rid of QD is a little bit different to the original paper [2], which did not stress the necessity of DR.
Thus, given $B < 0$ the extreme is a maximum. By contrast, if $B > 0$ we obtain a local minimum and $m_\phi^2$ is the mass square of the corresponding quantum in this vacuum. As expected, its mass is loop suppressed since it is the pseudo Goldstone boson of SI anomaly. This may interpret the lightness of the SM-like Higgs boson.

Applying the above results to the ISSM without any extension, one soon finds that $B < 0$ owing to the heaviness of top quark and its large internal degrees of freedom $n_i = -12$. To overcome it, naturally we introduce scalar or vector bosons which have large couplings to the SM Higgs doublet $\Phi$ [5]. A variant is the Higgs portal $\lambda X(\Phi \bar{\Phi})|X|^2$, which produces the ordinary Higgs mass term $m_\phi^2 = \lambda_X v_X^2 < 0$ with $v_X = \langle X \rangle$ via a hidden CW mechanism [6] (or hidden confining gauge dynamics [7]).

In this letter, it is found that the original version provides a predictive framework for DM.

**Accidental dark matter (aDM) from SI** DM guides us to new physics, nevertheless to too many directions thus lacking unambiguous predictions. What will happen when we embed DM into SISM?

Let us start from a toy SISM, that only includes singlet scalars $S_i$ to implement the CW mechanism. It has local symmetries $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$, Poincare and SI spacetime symmetries. They restrict the most general renormalizable potential to be

$$-\mathcal{L} = \frac{\lambda}{2} (\bar{\Phi} \Phi)^2 + \frac{\lambda_{ij}}{2} \Phi_i \Phi J^a_i S_j + \frac{\lambda_{ijkl}}{4!} S_i S_j S_k S_l,$$

(4)

with $i,... = 1, 2, ...N$. The singlets obtain masses through the second term, and thus it is convenient to work in the basis where they are diagonal, i.e, $\lambda_{ij} = \lambda \delta_{ij} > 0$. Remarkably, an accidental $Z_2$-symmetry, only $S_1$ odd under it, emerges. If only Higgs doublet acquires VEV, this $Z_2$ survives after EWSB. Consequently the lightest singlet, denoted by $S$, will be stable and service as a DM candidate. Such accidental DM stability is a reminiscence of proton stability in the SM, where the baryon number is accidentally conserved and protects proton stability due to its field content and symmetries. Stabilizing DM similarly is elegant, since we do not have to impose any ad hoc symmetry by hand.

On top of stability, other DM particle properties are largely specified. The single term $\lambda S_i^2 |\Phi|^2/2$ accounts for that. First, just like other massive members in the SM, DM acquires mass $m_{DM} = \sqrt{\lambda/2v}$ through EWSB. Next, interactions between DM and the visible particles are via the Higgs portal. The Higgs mediated DM-nucleon spin-independent cross section $\sigma_{SI} = 4 f_p^2 m_p^2 / \pi$, with $f_p$ the reduced mass of the proton-DM system and

$$f_p = \frac{\sqrt{\lambda}}{2v} \left( \sum_{\gamma = u,d,s} f_{T_\gamma}^{(n)} + 3 \right) \left( \sum_{\gamma = u,d,s} f_{T_\gamma}^{(n)} \right),$$

with $m_h = 125$ GeV and the values of the nucleon form factors $f_{T_\gamma}^{(n)}$ can be found in Ref. [8] (The updated data favors a smaller $f_{T_\gamma}^{(p)}$, but it does not affect our ensuing qualitative conclusions). $f_p$ has an unique dependence on $\lambda$. We can get a conservative upper bound $\lambda \lesssim 0.03$ from XENON100 [9]. It means that $m_{DM} \lessapprox 30$ GeV and then the Higgs invisible decay into a pair of $S$ kinematically opens and has a width

$$\Gamma(h \rightarrow SS) = \frac{1}{32\pi} \frac{\lambda^2 v^2}{m_h^2} \left( 1 - 2\alpha v^2/m_h^2 \right)^{1/2}.$$  

The SM Higgs width at 125 GeV is about 4.1 MeV. Thus, even if the branching ratio of invisible decay is allowed to be as large as 20%, we still get a more stringent upper bounds on $\lambda$ in turn DM mass:

$$\lambda \lesssim 0.013 \Rightarrow m_{DM} \lesssim 20.0 \text{GeV.}$$

That small coupling causes $S$ to annihilate ineffectively, and then fail to get correct relic density $\Omega_{DM} h^2 \simeq 0.1$ (see a relevant discussion [10]).

We argue that a singlet scalar is the unique candidate of aDM. Consider a fermionic singlet $\psi$. It fails because SI can not forbid the coupling $\bar{\psi} \Phi \psi$ which spoils the accidental $Z_2$. We can exhaust all possible DM candidate dwelling in a multiplet $(2j + 1, Q_Y)$ with $j$ an integer or half integer, which forms a representation of $SU(2)_L \times U(1)_Y$. There are some arguments against DM from $j \geq 1/2$ multiplets, in particular one is that the $Z$-boson mediated DM-nucleon SI scattering is too large. But it has a loophole, multiplets with $Q_Y = 0$ possessing no DM-DM-Z coupling. A rather strict no-go may be established as the following: (I) The Higgs doublet is the unique, at least dominant, source of DM mass via

Scalar DM $X \subset H$: $\frac{\lambda X}{2} |H|^2 (\Phi^0)^2$,

Fermionic DM $N$: $\lambda N \bar{N} \Phi \Phi$.

(8)

The fermionic DM is a Dirac particle because it must carry hypercharge, otherwise it can not couple to $\Phi$; (II) As in the toy model, the constraint from XENON100 and then the Higgs invisible decay forces $m_{DM}$ to lie well below $m_Z/2$; (III) Consequently, the invisible decay widths of $Z$-boson into the charged partners of DM are too large $^2$. In conclusion, only a real scalar singlet is the viable aDM candidate.

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$^2$ One may oppose that by adding operators $(H^\dagger T^a_p H)(\Phi^\dagger \tau^a \Phi)$,
Pin down aDM model We have shown that for aDM by SI, its quantum number, mass origin and interactions are almost fixed, leading to an unsuccessful toy model. We can cure it by considering non-singlet EWSB triggers. With them, DM gains effective annihilation channels. We have two choices, into a pair of photons/gluons at loop-level, or into the SM fermions at tree-level.

The former requires a quite large quartic coupling between DM and triggers, as jeopardizes perturbability of the model around the weak scale. What is more, such DM is excluded by the search of gamma-ray line or colored relics (the triggers must carry color thus being stable). Aside from these, they are likely to affect the Higgs production/decay rates too significantly. The $(2j+1, Q_Y)$ scalar trigger shifts the amplitude of Higgs to di-photon by an amount (normalized to the $W$-loop amplitude) \[ \frac{1}{24} \times \frac{7}{8} \sum_{n=1, \ldots, 2j} (j - n + Q_Y)^2. \] (9)

Thus, only these with $j \leq 1$ can change the Higgs to di-photon rate by less than 40%. In particular, for $(2, \pm 1/2)$ the corresponding change is about 7%.

So, we have to rely on the latter. By virtue of Eq. (9), three kinds of candidates are left, $(3, 0)$, $(3, \pm 1)$ and $(2, \pm 1/2)$. Triplets allow non-accidental $Z_2$ couplings and hence the doublets are unique candidates. Further using the economic criteria, we eventually pine down the model: two-Higgs-doublets plus a real singlet (2HDM+S). There are different versions of 2HDM classified by the pattern of couplings between the extra doublet and SM fermions [12]. For each version, DM has proper annihilating channels into the SM fermions. For definiteness, here we focus on type-II, where $\Phi_{1,2}$ couple to the up-type and down-type quarks (and leptons), respectively. Its general tree-level potential is given by

$$ V_0 = \frac{1}{2} \sum_{i,j}^{1,2} \lambda_{ij} |\Phi_i|^2 |\Phi_j|^2 + \sum_{i,j}^{1,2} 2 \lambda_{ij} |\Phi_i|^2 \text{Re}(\Phi_i^\dagger \Phi_j) $$

$$ + \lambda_1 |\Phi_1^\dagger \Phi_2|^2 + \lambda_2 \text{Re}(\Phi_1^\dagger \Phi_2^\dagger \Phi_1 \Phi_2) $$

$$ + \frac{\eta_1}{2} S^2 |\Phi_1|^2 + \eta_{12} S^2 \text{Re}(\Phi_1^\dagger \Phi_2) + \frac{\eta_2}{4} S^4 \] (10)

Here $\lambda_{ij} = \lambda_{ji}$ and we have assumed real parameters. $\Phi_{1,2}$ develop VEVs to account for the fermion masses.

As usual, we define $\tan \beta \equiv (\Phi_1^\dagger / \Phi_2)$ as $v_1 / v_2$. Viewing from the current Higgs data, which favors a quite SM-like Higgs boson, it is reasonable to consider the decoupling limit of the 2HDM. Then we have a large $\tan \beta \gtrsim 10$ thus a small $v_2 \lesssim 20$ GeV. Later it is found that a large $\tan \beta$ is also favored to enhance the DM annihilation rate.

Before heading towards the details of EWSB through the CW mechanism, we first make some reasonable simplifications. The singlet $S$ cannot acquire a VEV. For the doublets, $\Phi_1$ is the dominant source of EWSB while $\Phi_2$, the unique trigger, its VEV $v_2$ should be sufficiently small for the sake of DM and Higgs phenomenologies. Such vacuum configuration can be arranged by a small $\lambda_{12}$, which drives $\Phi_2$ away from the origin via a tadpole term of $\Phi_2$. In that limit ($\Phi_2$) locates at

$$ v_2 \simeq \frac{-\lambda_{12}}{\lambda_{12}} v_1 = v_1 / \tan \beta \ll v_1. \] (11)

With them, it is justified to approximately study EWSB similar to the original CW analysis based on the SM, i.e., with one Higgs doublet $\Phi_1$, and $\Phi_2$ is merely a trigger. Then the (Higgs) field-dependent masses of $\Phi_2$ are:

$$ m_C^2 = \lambda_{12} \frac{h^2}{2}, \quad m_H^2 = (\lambda_{12} + \lambda_1 + \lambda_2) \frac{h^2}{2}, \] m_A^2 = (\lambda_{12} + \lambda_1 - \lambda_2) \frac{h^2}{2}. \] (12)

We have decomposed fields as $\Phi_1^T = ((h + i G^0) / \sqrt{2}, G^-)$ and $\Phi_2^T = ((H + i A) / \sqrt{2}, C^-)$, with $G^0, C^-$ the Goldstones bosons. $\lambda_2$-dominance renders either $H$ or $A$ tachyonic. $\lambda_1$-dominance causes large mass splitting between the neutral and charged components, which implies a large violation of EW precise test. Therefore, $\lambda_{12}$-dominance is the favored case where $\lambda_{12}$ and $\lambda_{12}$ play the main roles in determining the vacuum.

The results The model mainly is described by only four parameters, $\lambda_{12}$, $\lambda_{12}$ (traded with $\tan \beta$ using Eq. (11)), $\eta_1$ and $\eta_2$. Higgs and DM phenomenologies tightly constrains them, leading to a quite predictive aDM.

Consider the SM-like Higgs boson mass $m_h$, which can largely determines $\lambda_{12}$. In the basis (Re$\Phi_1$, Re$\Phi_2$)$^T$, the CP-even Higgs mass square matrix $M_H^2$ has entries

$$ (M_H^2)_{11} \approx 8 B v^2 \left(1 + 3 \lambda_{12} \cot^2 \beta / 8 B\right), $$

$$ (M_H^2)_{22} \approx 12 v^2 / 2, \quad (M_H^2)_{12} \approx -\lambda_{12} v^2 \cot \beta / 2. \] (13)

with $B \approx (\lambda_{12}^2 - 3 y_t^2) / 64 \pi^2$. In the large $\tan \beta$ limit, we have $m_h \approx (M_H^2)^{1/2} \approx 125$ GeV, thus

$$ \lambda_{12} \approx 4.83 - 118.32 \cot^2 \beta. \] (14)

Even if $\tan \beta$ is as low as 10, we still need $\lambda_{12} \approx 4.0$. With that large coupling at the scale $Q = v$, resummation of the logarithmic $\lambda_{12} \log \phi_c / Q$ may cause an appreciable numerical modification.

To estimate this effect, we turn to the renormalization group equation (RGE)-improved effective potential [4, 13]. Only the running of $\lambda_{12}$ and $\lambda_{11}$ which determines the shape of $V_{\text{eff}}$ is took into account. Their RGEs satisfy $d\lambda / dt = \beta$ with $t = \log \phi_c / v$ and the one-loop which however produce mass splittings $\propto Q H v^2 / m_{DM}$, with $Q H$ the charge of $H$—components under $T_{\text{DM}}$. Thus some components will become even lighter.
beta functions
\begin{align}
16\pi^2 \beta_{\lambda_1} &= 12\lambda_1^2 + 4\lambda_2^2, \\
16\pi^2 \beta_{\lambda_2} &= 6\lambda_1\lambda_2 + 4\lambda_2^2,
\end{align}

(15)

where only terms of numerical importance are included. In the RGE-improved effective potential, the curvature becomes larger and accordingly the needed \( \lambda_{12} \) becomes smaller. The concrete value depends on the input \( \lambda_{12} \) via Eq. (14), but typically is small, \( \sim 5\% \). Note that at \( Q = v \) we have \( \beta_{\lambda_{12}} \) approaching 1, which means that at the TeV scale \( \beta_{\lambda_{12}} \) will exceed 1 and then perturbativity breaks down there.

Now we consider the DM phenomenologies. With \( v_2 \neq 0 \), DM mass receives several contributions:

\[ m_{DM}^2 = \frac{v^2}{2} \left( \eta_1 \sin^2 \beta + \eta_2 \cos^2 \beta + \eta_{12} \sin 2\beta \right), \]

(16)

with the \( \eta_2 \)-term negligible. For a light DM\textasciitilde10 GeV, the \( \eta_{12} \)-term in Eq. (10) provides an effective annihilation channel into \( b\bar{b} \) mediated by \( H \) in the \( s \)-channel. The thermally averaged cross section is

\[ \sigma v_{\text{ann}} = \frac{N_b \eta_{12} m_b^2}{4\pi m_H} \tan^2 \beta \left( 1 - m_b^2/m_{DM}^2 \right)^{3/2} \]

\[ = 2.4 \left( \frac{\eta_{12}}{0.04} \right) \left( \frac{\tan \beta}{20} \right)^2 \left( \frac{370 \text{ GeV}}{m_H} \right)^4 \text{ pb}, \]

(17)

taking \( m_{DM} = 10.0 \text{ GeV} \). The large \( \tan \beta \) enhancement is manifested, and it is just the reason why aDM succeeds here. On the other hand, \( \sigma_{SI} \) from the \( H \) contribution is suppressed. Actually, due to the cross symmetry their ratio is fixed up to DM mass:

\[ \frac{\sigma_{SI}}{\sigma v_{\text{ann}}} \approx 0.062 \times \left( \frac{m_{\nu\mu}}{m_{DM}m_b} \right)^2 \left( 1 - \frac{m_b^2}{m_{DM}^2} \right)^{-\frac{3}{2}}. \]

(18)

For \( m_b \lesssim m_{DM} \lesssim 10 \text{ GeV} \), typically \( \sigma_{SI} \) should be larger than a few \( 10^{-5}\sigma_{v_{\text{ann}}} \). It is on the edge of the exclusion lines of XENON10 and in particular LUX [14], however interestingly close to the value to explain the CoGeNT anomaly, which hinted a 8 GeV DM with \( \sigma_{SI} \sim 10^{-5} \text{ pb} \) [15]. Further experimental progress is expected to clear the confusing picture in the low DM mass region. In Fig. 1 we display the status of aDM, using micrOMEGAs 3.1 [16] for complete numerical analysis.

**Comments on the heavy Higgs states at LHC** The 2HDM in this paper has two features, a large \( \tan \beta \) and heavy Higgs states around \((\lambda_{12}/2)^{1/2} v \simeq 370 \text{ GeV} \). They can be searched at LHC. Due to large \( \tan \beta \), the production cross section of \( H \), associated with \( b\bar{b} \), is enhanced and moreover \( H \) dominantly decays into \( b\bar{b} \). Thus, multi-\( b \) jet is a promising signature to hunt such a Higgs. The present 7 TeV CMS data already has sensitivity to it [17] and the full 8 TeV data set of 25 fb\(^{-1} \) is able to exclude \( \tan \beta \gtrsim 20 \) [18]. In addition, a large \( \lambda_{12} \) enhances the branching ratio of \( H \) decay into a pair of SM-like Higgs bosons:

\[ \text{Br}(H \to hh) \approx \frac{1}{8N_b} \left( \frac{\lambda_{12} v^2}{\tan^2 \beta m_H m_b} \right)^2. \]

(19)

which can be 10\% for \( \tan \beta \simeq 10 \), giving rise to a remarkable \( b\bar{b} \)-jets signature.

**Conclusions** SI may provide a simple way to address the Higgs naturalness problem. We explore the idea of accidental DM in the SISM to find that 2HDM+S is the unique model that can give rise to acceptable DM phenomenologies. We study the type-II, which gives two clear predictions: A scalar DM about 5 GeV and heavy Higgs states about 370 GeV. They can be examined soon both from DM detections and LHC searches. Actually, the real singlet scalar DM, because of its simplicity, is extensively studied based on SM [19] or 2HDM [20]. But here we reveal that this somewhat trivial particle has depth, associated with naturalness of Higgs.

**ACKNOWLEDGEMENTS**

We would like to thank P. Ko for helpful discussions. This research was supported in part by the China Postdoctoral Science Foundation (No. 2012M521136) (ZK).

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1. E-mail: hustgj@itp.ac.cn
2. E-mail: zhaofengkang@gmail.com
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