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DARK MATTER IN THE ECONOMICAL 3-3-1 MODEL

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Abstract. *In this work we show that the economical 3-3-1 model has a dark mater candidate. It is a real scalar H_1^0 in which main part is bilepton (with lepton number 2) and its mass is in the range of some TeVs. We calculate the relic abundance of H_1^0 dark matter by using MicrOMEGAs 2.4 and figure out parameter space satisfying WMAP constraints.*

I. INTRODUCTION

We just know only 4% particles in our universe. The dominate component (about 74%) is called dark energy and dark matter (DM) makes about 22%. The natural of DM is still mysterious. There is no DM candidate in standard model (SM). To study DM, we need to extend the SM. In particular, there exists a simple extension of the SM gauge group to $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$, the so called 3-3-1 models. In this work we will concentrate on the economical 3-3-1 model, which contains very simple Higgs sector with two Higgs scalar triplets only. Such a scalar sector is minimal.

II. A REVIEW OF THE ECONOMICAL 3-3-1 MODEL

II.1. Particle content

The particle content in this model, which is anomaly free, is given as follows

$$\begin{aligned}
\psi_{aL} &= (\nu_{aL}, l_{aL}, (\nu_{aR})^c)^T \sim (3,-1/3), \quad l_{aR} \sim (1,-1), \quad a=1,2,3,\\
Q_{1L} &= (u_{1L}, d_{1L}, U_L)^T \sim (3,1/3)\,,\\
Q_{\alpha L} &= (d_{\alpha L}, -u_{\alpha L}, D_{\alpha L})^T \sim (3^*,0), \quad D_{\alpha R} \sim (1,-1/3)\,, \quad \alpha = 2,3,\\
u_{aR} &\sim (1,2/3)\,, \quad d_{aR} \sim (1,-1/3)\,, \quad U_R \sim (1,2/3)\,,
\end{aligned} \tag{1}$$

where the values in the parentheses denote quantum numbers based on the $(\mathrm{SU}(3)_L, \mathrm{U}(1)_X)$ symmetry. The electric charges of the exotic quarks U and D_α are the same as of the usual quarks, i.e., $q_U = 2/3$, $q_{D_\alpha} = -1/3$.

The spontaneous symmetry breaking in this model is obtained by two stages:

$$\mathrm{SU}(3)_L \otimes \mathrm{U}(1)_X \to \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_Q. \tag{2}$$

The first stage is achieved by a Higgs scalar triplet with a VEV given by

$$\chi = \left(\chi_1^0, \chi_2^-, \chi_3^0\right)^T \sim (3,-1/3)\,, \quad \langle\chi\rangle = \frac{1}{\sqrt{2}}\,(u,0,\omega)^T\,. \tag{3}$$

The last stage is achieved by another Higgs scalar triplet needed with the VEV as follows

$$\phi = \left(\phi_1^+, \phi_2^0, \phi_3^+\right)^T \sim (3, 2/3), \quad \langle\phi\rangle = \frac{1}{\sqrt{2}}(0, v, 0)^T. \tag{4}$$

The Yukawa interactions which induce masses for the fermions can be written in the most general form:

$$\mathcal{L}_{\mathrm{Y}} = \mathcal{L}_{\mathrm{LNC}} + \mathcal{L}_{\mathrm{LNV}}, \tag{5}$$

in which, each part is defined by

$$\begin{aligned}
\mathcal{L}_{\mathrm{LNC}} &= h^U \bar{Q}_{1L}\chi U_R + h^D_{\alpha\beta}\bar{Q}_{\alpha L}\chi^* D_{\beta R} \\
&\quad + h^l_{ab}\bar{\psi}_{aL}\phi l_{bR} + h^\nu_{ab}\epsilon_{pmn}(\bar{\psi}^c_{aL})_p(\psi_{bL})_m(\phi)_n \\
&\quad + h^d_a\bar{Q}_{1L}\phi d_{aR} + h^u_{\alpha a}\bar{Q}_{\alpha L}\phi^* u_{aR} + H.c., \qquad (6) \\
\mathcal{L}_{\mathrm{LNV}} &= s^u_a\bar{Q}_{1L}\chi u_{aR} + s^d_{\alpha a}\bar{Q}_{\alpha L}\chi^* d_{aR} \\
&\quad + s^D_\alpha\bar{Q}_{1L}\phi D_{\alpha R} + s^U_\alpha\bar{Q}_{\alpha L}\phi^* U_R + H.c., \qquad (7)
\end{aligned}$$

where p, m and n stand for $\mathrm{SU}(3)_L$ indices.

The VEV ω gives mass for the exotic quarks U, D_α and the new gauge bosons Z', X, Y, while the VEVs u and v give mass for the quarks u_a, d_a, the leptons l_a and all the ordinary gauge bosons Z, W [2]. To keep a consistency with the effective theory, the VEVs in this model have to satisfy the constraint

$$u^2 \ll v^2 \ll \omega^2. \tag{8}$$

II.2. Stable Higgs boson

In this model, the most general Higgs potential has very simple form [3]

$$\begin{aligned}
V(\chi,\phi) &= \mu_1^2\chi^\dagger\chi + \mu_2^2\phi^\dagger\phi + \lambda_1(\chi^\dagger\chi)^2 + \lambda_2(\phi^\dagger\phi)^2 \\
&\quad + \lambda_3(\chi^\dagger\chi)(\phi^\dagger\phi) + \lambda_4(\chi^\dagger\phi)(\phi^\dagger\chi). \qquad (9)
\end{aligned}$$

As usual, we first shift the Higgs fields as follows:

$$\chi = \begin{pmatrix} \chi_1^{P0} + \frac{u}{\sqrt{2}} \\ \chi_2^- \\ \chi_3^{P0} + \frac{\omega}{\sqrt{2}} \end{pmatrix}, \quad \phi = \begin{pmatrix} \phi_1^+ \\ \phi_2^{P0} + \frac{v}{\sqrt{2}} \\ \phi_3^+ \end{pmatrix}. \tag{10}$$

The subscript P denotes *physical* fields as in the usual treatment. Moreover, we expand the neutral Higgs fields as

$$\chi_1^{P0} = \frac{S_1 + iA_1}{\sqrt{2}}, \quad \chi_3^{P0} = \frac{S_3 + iA_3}{\sqrt{2}}, \quad \phi_2^{P0} = \frac{S_2 + iA_2}{\sqrt{2}}. \tag{11}$$

We get three massive physical particles from the Higgs sector, which are H^0, H_1^0, and H_2^+. In the effective approximation $w \gg v, u$,

$$\begin{aligned}
H^0 &\sim S_2, \quad H_1^0 \sim S_3, \quad G_4 \sim S_1, \\
H_2^+ &\sim \phi_3^+, \quad G_5^+ \sim \phi_1^+, \quad G_6^+ \sim \chi_2^+. \qquad (12)
\end{aligned}$$

From the Higgs gauge interactions given in [3], the coupling constants of H_1^0 Higgs and SM gauge bosons depend on s_ζ with $t_{2\zeta} = \frac{\lambda_3 M_W M_X}{\lambda_1 M_X^2 - \lambda_2 M_W^2}$. In the $w \gg v, u$ limit, $M_X \gg M_W$ or

$|t_{2\zeta}| \to 0$. Therefore, the H_1^0 Higgs does not interact with the SM gauge bosons $W^{\pm}, Z^0, \gamma$. However, there are couplings of H_1^0 Higgs with the Bilepton Y and Z'. In order to forbid the decay of H_1^o, we assume that $M^2_{H_1^0} \le M_Y^2$. It means that $2\lambda_1\omega^2 \le \frac{1}{4}g^2\omega^2$ or $\lambda_1 \le 0.051$. The interactions of H_1^0 Higgs with new gauge boson Z' is $Z' - H_1^0 - G_3$ interaction. But G_3 is a Goldstone bosons, this interaction can be gauged away by a unitary transformation.

Let us consider the interaction of the dark matter to Higgs bosons. From the Higgs potential (9), there exists the coupling of the new Higgs H_1^0 with H^0, H^0. So H_1^0 can decay into H^0, H^0. The lifetime is the inversion of decay rate $\tau = \frac{\hbar}{\Gamma}$. In order to get the constraint on the lifetime of H_1^0 larger than our universe's age, it is easy to see that the value of λ_3 is approximately order of 10^{-24}. It is to be emphasized that the limit of λ_3 makes sure that t_ζ is small.

To avoid H_1^0 decaying into H_2^+, H_2^-, we need the constraint for the mass of two Higgs, namely $M^2_{H_1^0} < 4M^2_{H_2^+}$. It means that $\lambda_1 < \lambda_4$. From the Lagrangian given in (5), it is easy to see that the H_1^0 does not interact with the SM leptons but it interacts with exotic quarks. As we know the exotic quarks are heavy ones, we assume that their masses are heavier than that of H_1^0. In brief, to get the stable Higgs particle H_1^0, we need the constraints as follows

$$\lambda_1 < \lambda_4, \quad \lambda_1 \le 0.051, \quad |\lambda_3| \sim 10^{-24}, \quad M_{H_1^0} \le M_U. \tag{13}$$

III. IMPLICATION FOR PARAMETER SPACE FROM WMAP

In this section, we discuss constraints on the parameter space of the 3-3-1 model originating from the WMAP results on dark matter relic density [4]. In order to calculate the relic density, we use micrOMEGAs 2.4 [5] after implementing new model files into CalcHEP [6]. The parameters of our model are the self-Higgs couplings, $\lambda_1, \lambda_2, \lambda_3, \lambda_4$, the VEV w and exotic quarks masses. The relic density does not depend on λ_2 and changes a little when varying λ_4. First, we fix the values of $\lambda_{2;3;4}$ satisfying the constraints given in (13), especially taking $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}, \lambda_4 = 0.06$ and varying the remaining parameters. We consider the relic density as a function of λ_1. Fig. (1) compares the WMAP data to the theoretical prediction. The dashed red line presents prediction by our theory by fixing $M_{D_2} = M_{D_3} = 100$ TeV , w=10 TeV, and $M_U = 24$ TeV. In order to meet fully the WMAP dada, the value of λ_1 must be different from the allowed value in (13). However, if we change the mass of exotic quark, we can obtain allowed region, namely the dot-dashed green line given by taking $w = 10$ TeV, $M_U = 36$ TeV. The allowed region of λ_1 satisfy both the WMAP data and the stable Higgs constraints (13) is $0.0393 < \lambda_1 < 0.0406$. The full orange line is obtained by fixing $w = 30$ TeV and $M_U = 36$ TeV. In this case, the constraints on λ_1 is $0.0424 < \lambda_1 < 0.0436$. On the other hand, if we vary the masses of exotic $D-$ quarks, we can find the other allowed region of λ_1. For example, if we take $M_{D_2} = M_{D_3} = 12$ TeV the allowed region of λ_1 is $0.0502 < \lambda_1 < 0.051$. Hence, we could conclude that the mass exotic $U-$ quark can be larger or smaller than that of $D-$ quarks in order to come to agreement with the WMAP data.

Let us consider allowed region of ω, fig. (2) shows the dependence of the relic density on the VEV w for $\lambda_1 = 0.04$, $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}$, $\lambda_4 = 0.06$. This figure shows that the VEV $w < 15.33$ TeV is in the WMAP-allowed region for $M_U = 36$ TeV, $M_{D_2}= M_{D_3}$ $=100$ TeV. However, if the values of $M_U = 24$ TeV or $M_D = M_U = 36$ TeV, there is no allowed region of ω in agreement with the WMAP data. It is totally difference for $M_U =$ 70 TeV and $M_{D_2} = M_{D_3} = 12$ TeV (large dashing brown line). The relic density firstly increases then decreases as a function of w. In the WMAP band, w is in the range 8.752 - 13.85 GeV or 23.3 - 24.61 GeV.

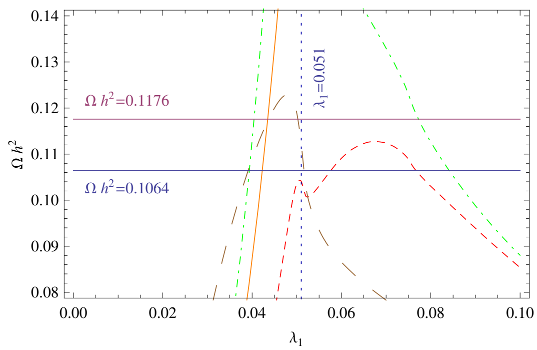

Fig. 1. Ωh^2 vs λ_1 for $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}$, $\lambda_4 = 0.06$, M_{D_2} $=M_{D_3}$$=100$ TeV, for w=10 TeV, $M_U = 24$ TeV (dashed red line), for $w = 10$ TeV, $M_U = 36$ TeV (dot-dashed green line), for $w = 30$ TeV, $M_U = 36$ TeV (full orange line), for M_{D_2} $= M_{D_3} = 12$ TeV, $w = 10$ TeV, $M_U = 70$ TeV (large dashing brown line). Dotted blue constant line is corresponding to $\lambda_1 = 0.051$.

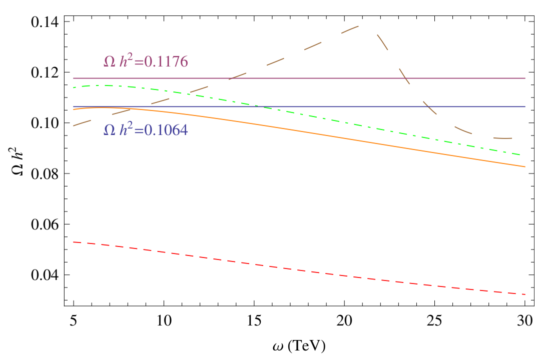

Fig. 2. Ωh^2 vs w for $\lambda_1 = 0.04$, $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}$, $\lambda_4 = 0.06$, for $M_U =$ 24 TeV, $M_{D_2} = M_{D_3} = 100$ TeV (dashed red line), for $M_U = 36$ TeV, $M_{D_2} =$ $M_{D_3} = 100$ TeV (dot-dashed green line), for $M_U = M_{D_2} = M_{D_3} = 36$ TeV (full orange line), for $M_U = 70$ TeV, $M_{D_2} = M_{D_3} = 12$ TeV (large dashing brown line).

The relic density increases fast when M_U increases for $M_{D_2} = M_{D_3} = 100$ TeV while it becomes flat at high values of M_U for $M_{D_2} = M_{D_3} = 12$ TeV as shown in fig. (3). The region of M_U in the allowed WMAP band is $34.93 < M_U < 36.73$ TeV for $w = 10$ TeV, $M_{D_2} = M_{D_3} = 100$ TeV, $39.25 < M_U < 40.89$ TeV for $w = 30$ TeV, $M_{D_2} = M_{D_3} =$

100 TeV, $66.71 < M_U < 85.01$ TeV for $w = 10$ TeV, $M_{D_2} = M_{D_3} = 12$ TeV, and $97.64 < M_U < 217.8$ TeV for $w = 30$ TeV, $M_{D_2} = M_{D_3} = 12$ TeV.

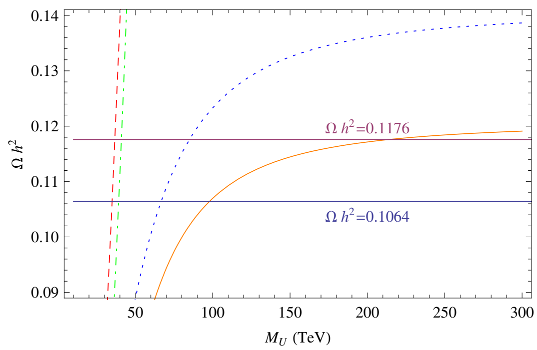

Fig. 3. Ωh^2 vs M_U for $\lambda_1 = 0.04$, $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}$, $\lambda_4 = 0.06$, for $w = 10$ TeV, $M_{D_2} = M_{D_3} = 100$ TeV (dashed red line), for $w = 30$ TeV, $M_{D_2} = M_{D_3} = 100$ TeV (dot-dashed green line), for $w = 10$ TeV, $M_{D_2} = M_{D_3} = 12$ TeV (dotted blue line), for $w = 30$ TeV, $M_{D_2} = M_{D_3} = 12$ TeV (full yellow line).

Next we study the variations of Ωh^2 as a function of M_{D_2} (see fig. (4)) and M_{D_3} (see fig. (5)). Fig. (4) shows the relic density increases to the maximum point then decreases as M_{D_2} increases; and the region of M_{D_2} in the WMAP limit is $37.99 < M_{D_2} < 259.7$ TeV for $M_U = 36$ TeV, $M_{D_3} = 100$ TeV. If $M_U = 70$ TeV, M_{D_2} is around 12 TeV or 100 TeV for $M_{D_3} = 12$ TeV, while for a larger value $M_{D_3} = 100$ TeV, M_{D_2} is around 12 TeV or 800 TeV. (Fig. 5) shows the variation of Ωh^2 as a function M_{D_3}. Ωh^2 increases then keeps up constant value. In case of $M_{D_2} = 12$ TeV, for $M_U = 36$ TeV, the relic density is always below the WMAP limit, while for $M_U = 70$ TeV, the relic density is always in the WMAP-allowed region.

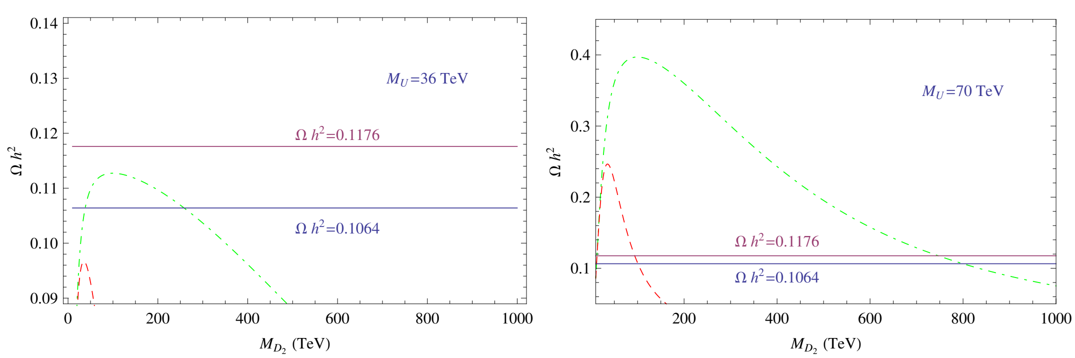

Fig. 4. Ωh^2 vs M_{D_2} for $\lambda_1 = 0.04$, $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}$, $\lambda_4 = 0.06$, $w = 10$ TeV, for $M_{D_3} = 100$ TeV (dot-dashed green line), for $M_{D_3} = 12$ TeV (dashed red line).

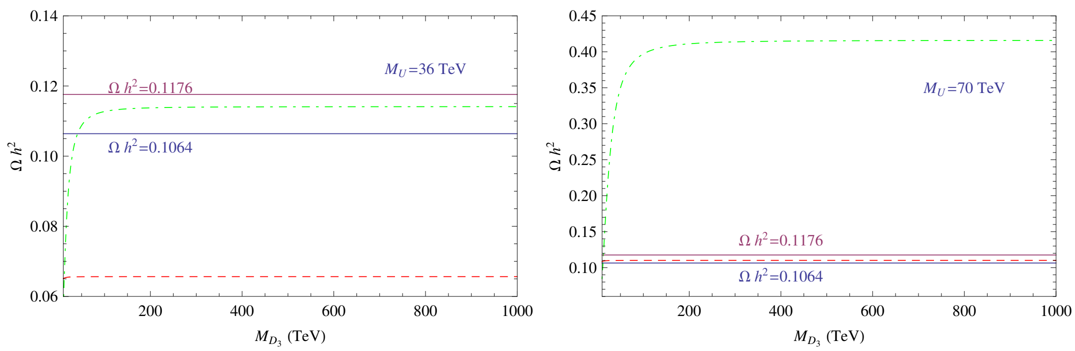

Fig. 5. Ωh^2 vs M_{D_3} for $\lambda_1 = 0.04$, $\lambda_2 = 0.12$, $\lambda_3 = -10^{-24}$, $\lambda_4 = 0.06$, $w = 10$ TeV, for $M_{D_2} = 100$ TeV (dot-dashed green line), for $M_{D_2} = 12$ TeV (dashed red line).

IV. CONCLUSION

We have shown that the economical 3-3-1 model provides a good candidate for dark matter called scalar Higgs H_1^0 without any discrete symmetry; and it just requires some constraints on Higgs couplings constant. To forbid the decay of H_1^0, we require that $\lambda_1 \leq 0.051$, $\lambda_1 < \lambda_4$, and $|\lambda_3| \sim 10^{-24}$. The parameter space has been studied in detail. Direct and indirect searches will be studied in near future.

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