Two-Step Cosmological Selection: Electroweak Scale and Its Unifying Legacy

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Contents

Motivation

Naturalness Problems in the SM:

- Fermion mass hierarchy

  Three generations of fermions share common gauge charges, but their masses span about 6 orders.

- Flavor mixing

  The origin of flavor mixings are not explained.

- Gauge hierarchy problem

  The EW VEV is so many orders of magnitude smaller than the Planck scale, and the Higgs mass is unprotected against large quantum corrections from higher scales.

- ...

Motivation

Our attempts to account for some Naturalness Problems:

- A new "texture-zero" form *JL. Y, HB. Z and TF. F, PLB 853, 138677 (2024)*

$$m_f = \begin{pmatrix} 0 & m_{f,12} & m_{f,13} \\ m^*_{f,12} & 0 & m_{f,23} \\ m^*_{f,13} & m^*_{f,23} & m_{f,33} \end{pmatrix} \tag{1}$$

- The flavor-dependent $U(1)_F$ model *JL. Yang, HB. Z and TF. F, EPJC 84, 616 (2024)*

  Local gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_F$

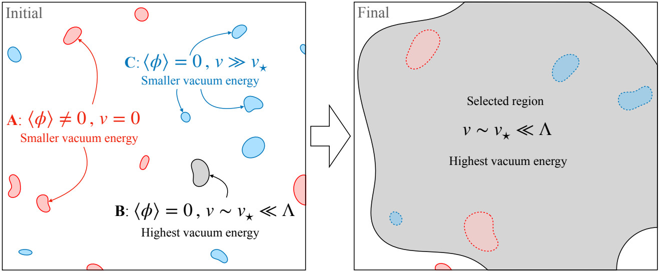
  New fields: H_2, H_3, Φ, ν_{R_1} ν_{R_2}

  - Explains the fermion hierarchy and flavor mixing naturally.
  - Accounts for the neutrino oscillations by Type-I seesaw.
  - Predicts testable neutrino transition MDM *JL. Yang, HB. Z and TF. F, PRD 110, 115007 (2024)* and Higgs phenomenology *Z. Cao, JL. Yang, TB. Hou and TF. Feng, PRD 113, 016012 (2026)*.

Motivation

Is there a better model?

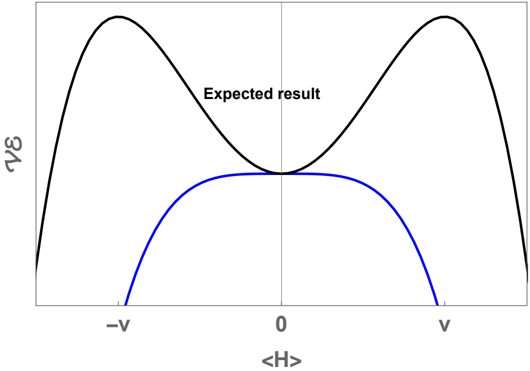
- SM local group and additional global $U(1)$
- H_2 and Φ
- The gauge hierarchy puzzle is also addressed?



Source: S. Chattopadhyay, DS. Chattopadhyay and RS. Gupta, PRL. 134, 241803 (2025)

Motivation

D: $\langle \phi \rangle = 0, \langle H \rangle = 0$?



The model

- The complex scalar singlet extended SM with global $U(1)_{B-L}$ symmetry

$$\begin{aligned}\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\mu_\Phi^2 \Phi\Phi^* - \frac{1}{4}\lambda_\Phi(\Phi\Phi^*)^2 - \lambda_{H\Phi}(\Phi\Phi^*)(H^\dagger H) - V_{\rm soft} \\ + Y_{ij}^R \Phi \bar{\nu}_{R_i}^c \nu_{R_j} + Y_{\alpha j}^D \bar{L}_\alpha H \nu_{R_j},\end{aligned} \tag{2}$$

where $\mu_\Phi^2 \gg \mu_H^2$ and

$$\begin{aligned}V_{\rm soft} = -\frac{1}{2}[\kappa_1^3\Phi + \kappa_2^2\Phi^2 + \kappa_3\Phi^3 + \kappa_4\Phi^2\Phi^* \\ + \kappa\Phi(H^\dagger H) + h.c.],\end{aligned} \tag{3}$$

The neutrino sector

- Tiny neutrino masses can be obtained after the spontaneously breaking of $U(1)_{B-L}$,

$$m_\nu = -M_D^T M_R^{-1} M_D, \tag{4}$$

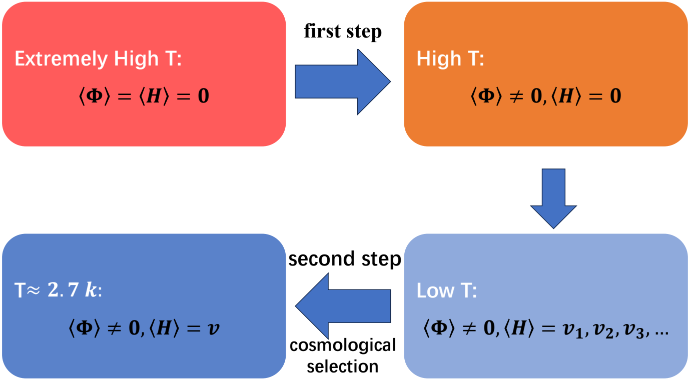
where

$$M_D = Y_D v, \;\; M_R = Y_R v_\phi . \tag{5}$$

- The observed baron asymmetry can be explained via leptogenesis with Type-I seesaw mechanism.

The two-step cosmological selection mechanism

- The two-step cosmological selection mechanism



Extremely High T:

$\langle \Phi \rangle = \langle H \rangle = 0$

first step

High T:

$\langle \Phi \rangle \neq 0, \langle H \rangle = 0$

Low T:

$\langle \Phi \rangle \neq 0, \langle H \rangle = v_1, v_2, v_3, \ldots$

second step

cosmological selection

T≈ 2.7 k:

$\langle \Phi \rangle \neq 0, \langle H \rangle = v$

$-\mu_H^2(T) = -\mu_H^2 + G_H T^2, -\mu_\Phi^2(T) = -\mu_\Phi^2 + G_\Phi T^2$, where $G_H \gg G_\Phi$

The two-step cosmological selection mechanism

The total vacuum energy density can be expressed as

$$\mathscr{V}\mathscr{E} = -\frac{1}{4}\lambda_H v_*^4 + \left(\frac{\kappa}{2v_\phi} - \lambda_{H\Phi}\right) v_\phi^2 v_*^2 - \frac{1}{4}\lambda_\phi v_\phi^4 - \frac{1}{2}\kappa_1^3 v_\phi + \frac{1}{2}(\kappa_3 + \kappa_4) v_\phi^3 \tag{6}$$

Maximizing $\mathscr{V}\mathscr{E}$ with respect to v_* yields

$$v_* = \sqrt{\frac{\frac{\kappa}{v_\phi} - 2\lambda_{H\Phi}}{\lambda_H}}\, v_\phi\,, \tag{7}$$

which requires $\frac{\kappa}{v_\phi} - 2\lambda_{H\Phi} > 0$.

The EW scale v_* is selected naturally by small κ and $\lambda_{H\Phi}$!

The two-step cosmological selection mechanism

Imposing $v_* = v \approx 246$ GeV, we obtain

$$\lambda_{H\Phi} = \frac{1}{2}\left(\frac{\kappa}{v_\phi} - \lambda_H \frac{v^2}{v_\phi^2}\right), \tag{8}$$

$$\mu_H^2 = -\kappa v_\phi, \tag{9}$$

$$\mu_\phi^2 = \lambda_\Phi v_\phi^2 - \lambda_H v^4/v_\phi^2 - 2\kappa_2^2 - 3(\kappa_3 + \kappa_4)v_\phi^2. \tag{10}$$

To avoid excessive fine-tuning, we impose

$$\kappa v_\phi < (10^3 M_h^2)/2 \approx (2.8\,\text{TeV})^2 \tag{11}$$

Dark matter phenomenology

DM mass and theoretical constraints

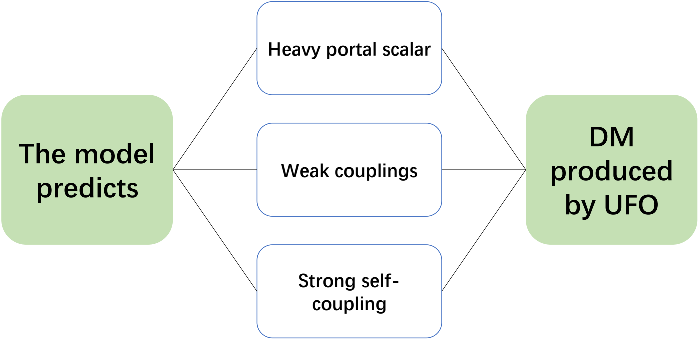
- Applying Eqs. (6-8), we can obtain the physical scalar mass square eigenvalues approximately as ($v_\phi \gg v$ is assumed)

$$\begin{aligned} M_h^2 &\approx 2\lambda_H v^2 \approx (125\,\mathrm{GeV})^2, \\ M_\phi^2 &\approx 2\lambda_\Phi v_\phi^2 + \frac{\kappa v^2}{v_\phi} + \frac{\kappa_1^3}{v_\phi} - 3(\kappa_3+\kappa_4)v_\phi, \\ M_A^2 &= \frac{\kappa v^2}{v_\phi} + \frac{\kappa_1^3}{v_\phi} + 4\kappa_2^2 + (9\kappa_3+\kappa_4)v_\phi. \end{aligned} \tag{12}$$

Dark matter phenomenology

DM production

- Ultra-relativistic Freeze-Out (UFO) during reheating *SE. Henrich, Y. Mambrini and KA. Olive, PRL 135, 221002 (2025)*


The model predicts

Heavy portal scalar

Weak couplings

Strong self-coupling

DM produced by UFO

Dark matter phenomenology

- The dominant DM production rate R_A arises from the processes $\phi\phi \to AA$ and $\phi \to AA$. Assuming $T \ll M_\phi$, we can obtain

$$R_A^{\phi\phi}(T) \approx \frac{\lambda_\Phi^2 T^2}{32\pi^5}\left(M_\phi \ln(1 - e^{\frac{M_\phi}{-T}}) - T\mathrm{Li}_2 e^{\frac{M_\phi}{-T}}\right)^2 \tag{13}$$

$$R_A^{\phi}(T) \approx \frac{\lambda_\Phi M_\phi^{\frac{5}{2}} T^{\frac{3}{2}} e^{\frac{M_\phi}{-T}}}{8(2\pi)^{\frac{5}{2}}}\left(1 - \frac{3T}{2M_\phi}\right) \tag{14}$$

- DM number density n_A can be calculated by solving the Boltzmann equation

$$\frac{dY_A}{da} = \frac{2a^2}{H(a)}\left(1 - \frac{Y_A^2}{(Y_A^{\mathrm{eq}})^2}\right)R_A, \tag{15}$$

where the comoving yield $Y_A \equiv n_A a^3$.

Dark matter phenomenology

- The DM mass with the present-day DM relic abundance $\Omega_A h^2 = 0.12$

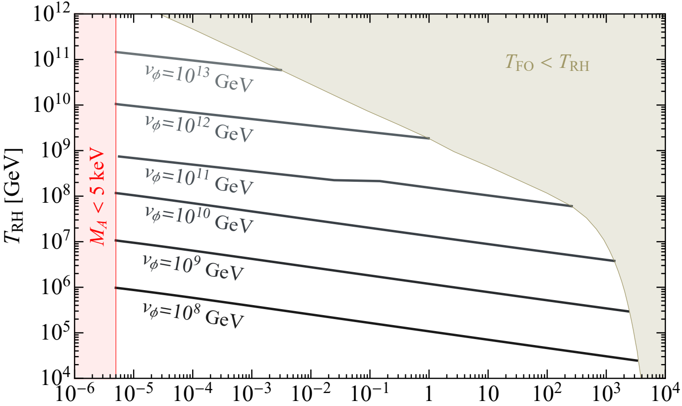
$$M_A \approx \frac{0.02\, T_{\mathrm{RH}}^3}{n_A(a_{\mathrm{RH}})}\ \mathrm{keV}. \tag{16}$$

- Taking the active neutrino mass equals to 0.01 eV, the life-time of DM decays to neutrinos can be estimated

$$\tau_A \approx \frac{1\ \mathrm{GeV}}{M_A}\left(\frac{v_\phi}{10^{12}\ \mathrm{GeV}}\right)^2 10^{23}\ \mathrm{sec}. \tag{17}$$

Dark matter phenomenology

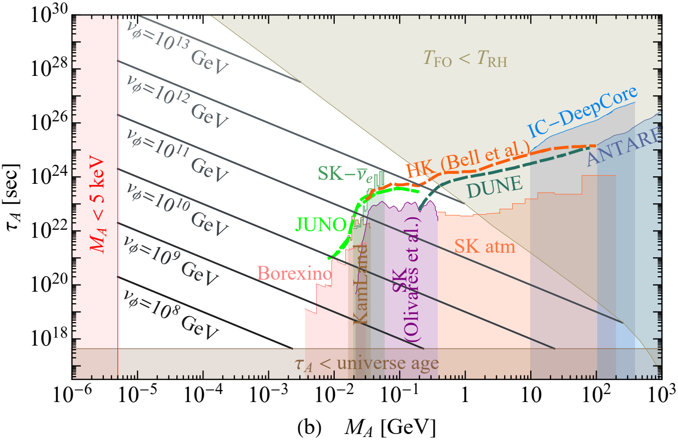
- Numerical results of DM relic abundance



(a) M_A [GeV]

Dark matter phenomenology

- Numerical results of DM life-time



Conclusions

By simply extending the SM, this work provides a unifying theory to address several fundamental puzzles in particle physics:

- A two-step cosmological selection mechanism is proposed to resolve the hierarchy problem without introducing severe fine-tuning.
- The observed neutrino oscillations and baryon asymmetry can be explained via type-I seesaw and leptogenesis respectively.
- A viable DM candidate is provided, where the DM abundance is produced via UFO during reheating and correlates directly with the reheating temperature.
- The predicted life-time of DM decays into the active neutrinos is testable at the next generation detectors.

Thank you!

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