



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

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May 18, 2026

In collaboration with Frank F. Deppisch (UCL) • Work in progress



NPhIS 2026

- Motivation
- The model
- The neutrino sector
- The two-step cosmological selection mechanism
- Dark matter phenomenology
- Conclusions

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.

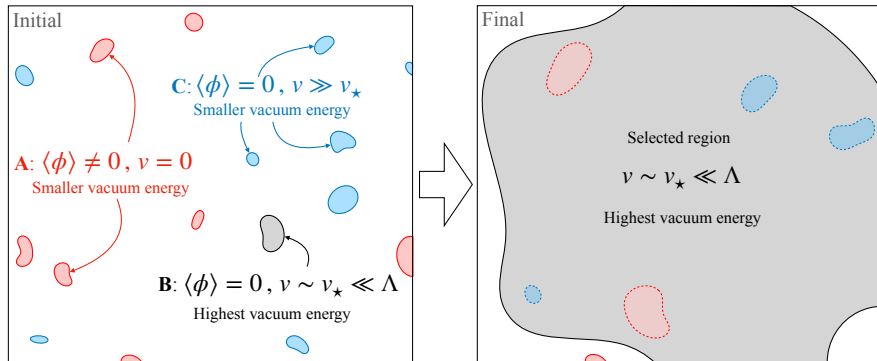
- Gauge hierarchy problem

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.

- ...

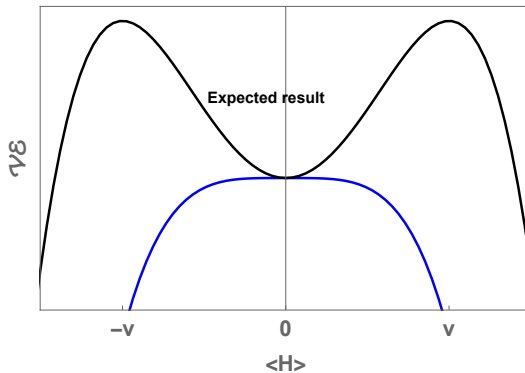
Theoretical solutions to the gauge hierarchy problem:

- Supersymmetry [P. Ramond, PRD 3, 2415 \(1971\)](#)
- Extra-dimension [N. Arkani-Hamed and et. al, PLB 429, 263 \(1998\)](#)
- Anthropic principle: Multiverse [V. Agrawal and et. al, PRD 57, 5480 \(1998\)](#)
 - Cosmological relaxation: The relaxion field rolls down a potential energy gradient in the early universe [P. W. Graham and et al., PRL 115, 221801 \(2015\)](#)
 - Crunching dilaton model: only small Higgs VEVs generate a metastable vacuum avoiding a cosmic crunch, enabling viable cosmic expansion [C. Csaki and et al., PRL 126, 091801 \(2021\)](#)
 - Cosmological selection: the regions with maximal vacuum energy will eventually dominate the multiverse in volume [S. Chattopadhyay and et al., PRL, 241803 \(2025\)](#)



Source: S. Chattopadhyay and *et al.*, PRL. 134, 241803 (2025).

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



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

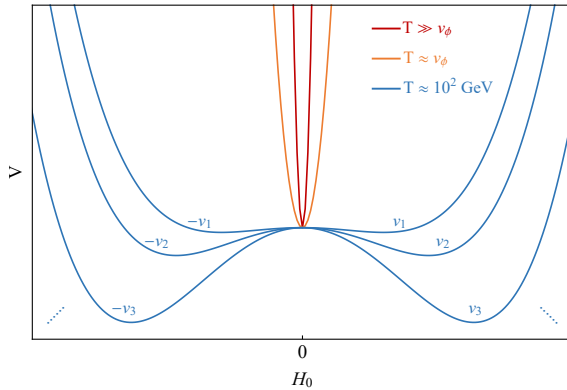
$$\begin{aligned} \mathcal{L} = \mathcal{L}_{\text{SM}} &+ \frac{1}{2}\mu_{\Phi}^2\Phi\Phi^* - \frac{1}{4}\lambda_{\Phi}(\Phi\Phi^*)^2 - \lambda_{H\Phi}(\Phi\Phi^*)(H^{\dagger}H) - V_{\text{soft}} \\ &+ Y_{ij}^R\Phi\bar{\nu}_{Ri}^c\nu_{Rj} + Y_{\alpha j}^D\bar{L}_{\alpha}H\nu_{Rj}, \end{aligned} \quad (1)$$

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

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

The two-step cosmological selection mechanism

- The scalar potential versus Higgs field value:



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

The two-step cosmological selection mechanism

The total vacuum energy density can be expressed as

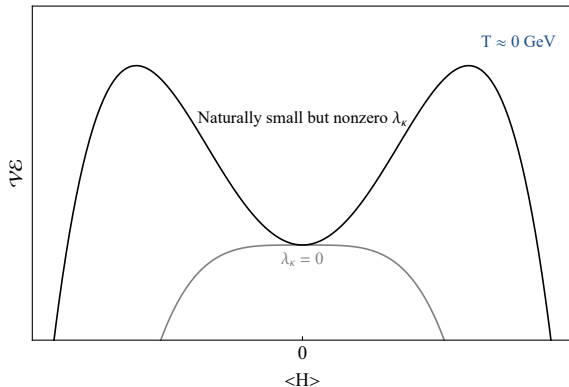
$$\begin{aligned} \mathcal{V}^{\mathcal{E}} = & -\frac{1}{4}\lambda_H v_*^4 + \left(\frac{\kappa}{2v_\phi} - \lambda_{H\Phi}\right)v_\phi^2 v_*^2 - \frac{1}{4}\lambda_\phi v_\phi^4 \\ & - \frac{1}{2}\kappa_1^3 v_\phi + \frac{1}{2}(\kappa_3 + \kappa_4)v_\phi^3 \end{aligned} \quad (3)$$

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

$$v_* = \sqrt{\frac{\lambda_\kappa}{\lambda_H}} v_\phi, \quad (4)$$

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

- The vacuum energy density versus the Higgs VEV:



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

$$\lambda_{H\Phi} = \frac{1}{2} \left(\frac{\kappa}{v_\phi} - \lambda_H \frac{v^2}{v_\phi^2} \right), \quad (5)$$

$$\mu_H^2 = -\kappa v_\phi, \quad (6)$$

$$\mu_\phi^2 = \lambda_\Phi v_\phi^2 - \lambda_H v^4 / v_\phi^2 - 2\kappa_2^2 - 3(\kappa_3 + \kappa_4) v_\phi^2. \quad (7)$$

To avoid excessive fine-tuning, we impose

$$\kappa v_\phi < (10^3 M_h^2) / 2 \approx (2.8 \text{ TeV})^2 \quad (8)$$

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

$$m_\nu = -M_D^T M_R^{-1} M_D, \quad (9)$$

where

$$M_D = Y_D v, \quad M_R = Y_R v_\phi. \quad (10)$$

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

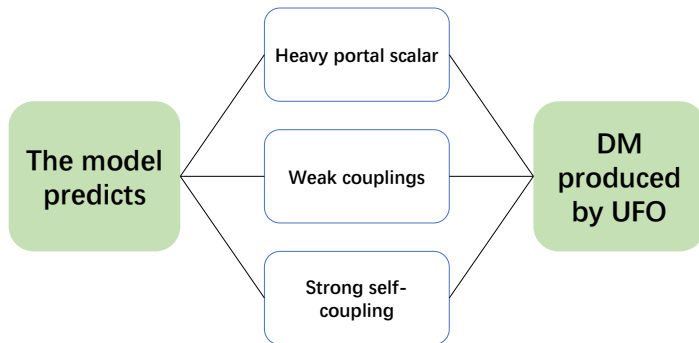
DM mass and theoretical constraints

- Applying Eqs. (5-8), we can obtain the physical scalar mass square eigenvalues approximately as ($v_\phi \gg v$ is assumed)

$$\begin{aligned}M_h^2 &\approx 2\lambda_H v^2 \approx (125 \text{ GeV})^2, \\M_\phi^2 &\approx 2\lambda_\Phi v_\phi^2 + \frac{\kappa v^2}{v_\phi} + \frac{\kappa_1^3}{v_\phi} - 3(\kappa_3 + \kappa_4)v_\phi, \\M_A^2 &= \frac{\kappa v^2}{v_\phi} + \frac{\kappa_1^3}{v_\phi} + 4\kappa_2^2 + (9\kappa_3 + \kappa_4)v_\phi.\end{aligned}\tag{11}$$

DM production

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



Dark matter phenomenology

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

$$R_A^{\phi\phi}(T) \approx \frac{\lambda_\phi^2 M_\phi T}{32\pi^5} \int_{s_{\min}}^{\infty} \sqrt{1 - 4M_\phi^2/T^2} K_1\left(\frac{\sqrt{s}}{T}\right) ds \quad (12)$$

$$R_A^\phi(T) \approx \frac{(\lambda_\phi v_\phi + 6\kappa_3 - 2\kappa_4)^2}{8\pi M_\phi} K_1(M_\phi/T) \quad (13)$$

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

$$\frac{dY_A}{da} = \frac{2a^2}{H(a)} \left(1 - \frac{Y_A^2}{(Y_A^{\text{eq}})^2}\right) R_A, \quad (14)$$

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

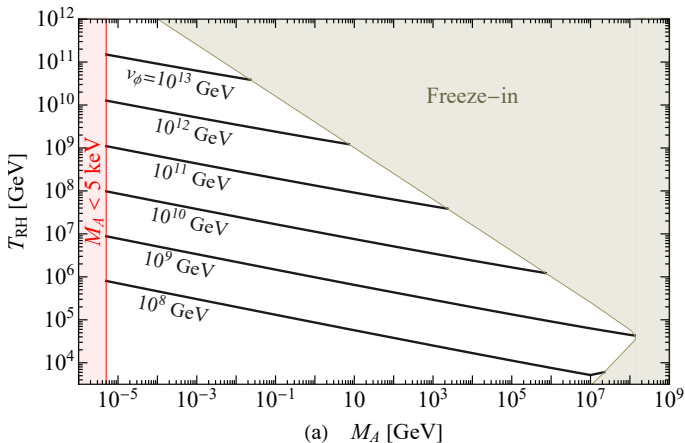
- The DM mass with the present-day DM relic abundance $\Omega_A h^2 = 0.12$

$$M_A \approx \frac{0.02 T_{\text{RH}}^3}{n_A(a_{\text{RH}})} \text{ keV}. \quad (15)$$

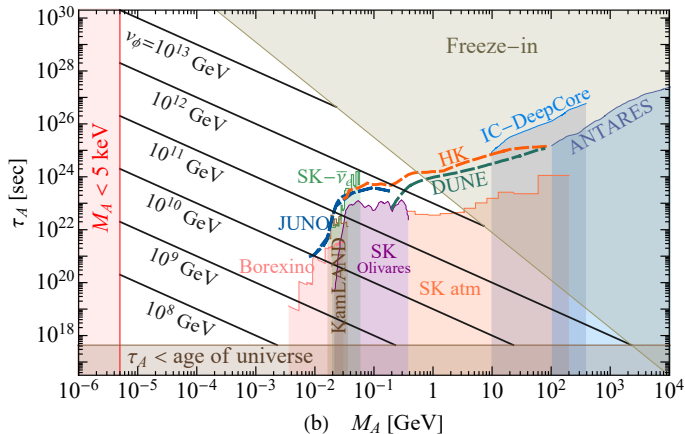
- Taking the active neutrino mass equals to 0.01 eV, the life-time of DM decays to neutrinos can be estimated

$$\begin{aligned} \tau_A &= \left[\frac{M_A}{4\pi v_\phi^2} \sum_{\alpha, \beta=1}^3 \left| \left(M_D^T \cdot M_R^{-1} \cdot M_D \right)_{\alpha\beta} \right|^2 \right]^{-1} \\ &= \frac{1 \text{ GeV}}{M_A} \frac{0.01 \text{ eV}^2}{\sum_{i=1}^3 m_{\nu_i}^2} \left(\frac{v_\phi}{10^{12} \text{ GeV}} \right)^2 \times 10^{23} \text{ sec}, \end{aligned} \quad (16)$$

- Numerical results of DM relic abundance



- Numerical results of DM life-time



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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 NPhIS 2026