Criticality as the origin of scales in particle physics

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Work in progress

My field: BSM phenomenology

- Left-right symmetric models, collider phenomenology
- SUSY + N_R , EDMs
- Flavour anomalies
- DM model building
- Cosmic ray data (Pamela, Fermi etc), DM indirect and direct detection
- Primordial black holes, GW detection and phenomenology
- DESI, evolving Dark Energy

Outline

Aim: Explain hierarchies in physical scales

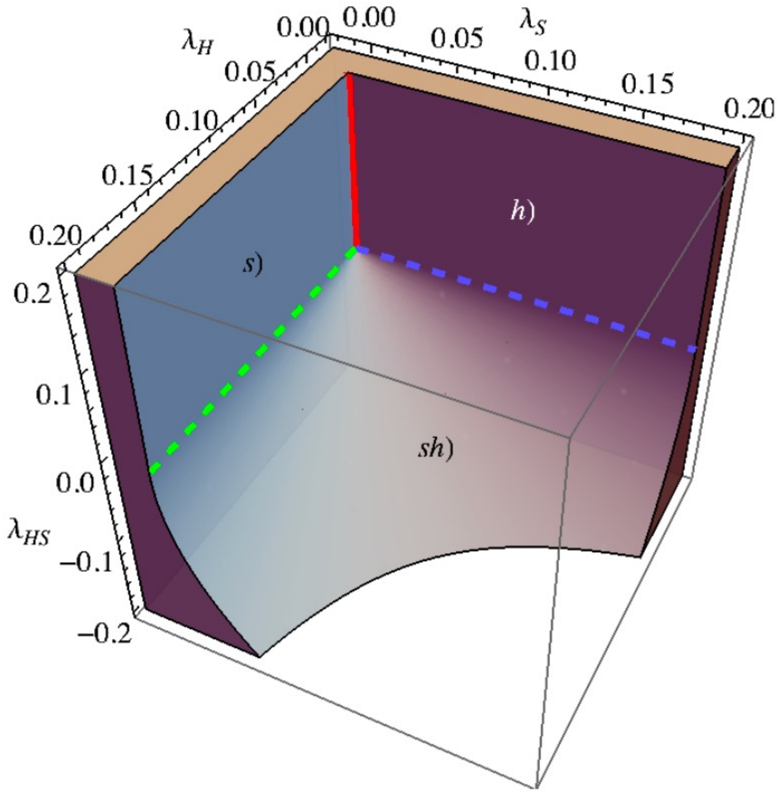
- Coleman-Weinberg mechanism with small couplings (introduce a concept of multi-phase criticality)
- Freeze-out in DM induced dynamical symmetry breaking
- Freeze-in in DM induced dynamical symmetry breaking
- DM induced dynamical symmetry breaking in naturally hierarchical and stable model of all known particle physics

There is only one, HIGH scale for all particle physics

The SM scale is loop suppressed compared to the scale

The hierarchies in physical phenomena come from
1) loops and
2) from the hierarchy in small dimensionless couplings

Classically scale invariant Higgs-Dilaton model



$$V = \lambda_H |H|^4 + \lambda_{HS}|H|^2 \frac{s^2}{2} + \lambda_S \frac{s^4}{4}$$

- Phase $s)$ $s \neq 0$ and $h = 0$

$$\lambda_S = 0$$

- Phase $h)$ $h \neq 0$ and $s = 0$

- Phase $sh)$ $s, h \neq 0$

$$2\sqrt{\lambda_H \lambda_S} + \lambda_{HS} = 0$$

- Multi-phase criticality: masses and mixings vanish

$$\lambda_S(\bar{\mu}) = \lambda_{HS}(\bar{\mu}) = 0,$$

CW mechanism and multi-phase criticality

- Dynamical symmetry breaking around the MP criticality: GW not good

$$V^{(1)}|_{\overline{\rm MS}} = \frac{1}{4(4\pi)^2}\,{\rm Tr}\left[M_S^4\left(\ln\frac{M_S^2}{\bar\mu^2}-\frac{3}{2}\right)+ -2M_F^4\left(\ln\frac{M_F^2}{\bar\mu^2}-\frac{3}{2}\right)+3M_V^4\left(\ln\frac{M_V^2}{\bar\mu^2}-\frac{5}{6}\right)\right] \quad (10)$$

$$s \approx e^{-1/4}s_S, \qquad h \approx \frac{e^{-1/4}s_S}{4\pi}\sqrt{\frac{-\beta_{\lambda_{HS}}\ln R}{2\lambda_H}},$$

$$R = e^{-1/2}s_S^2/s_{HS}^2$$

β-function suppressed $\quad m_s^2 \approx \frac{2s^2\beta_{\lambda_S}}{(4\pi)^2}, \qquad m_h^2 \approx \frac{-s^2\beta_{\lambda_{HS}}\ln R}{(4\pi)^2} = 2\lambda_H h^2$ $\quad$ ***β***-function suppressed

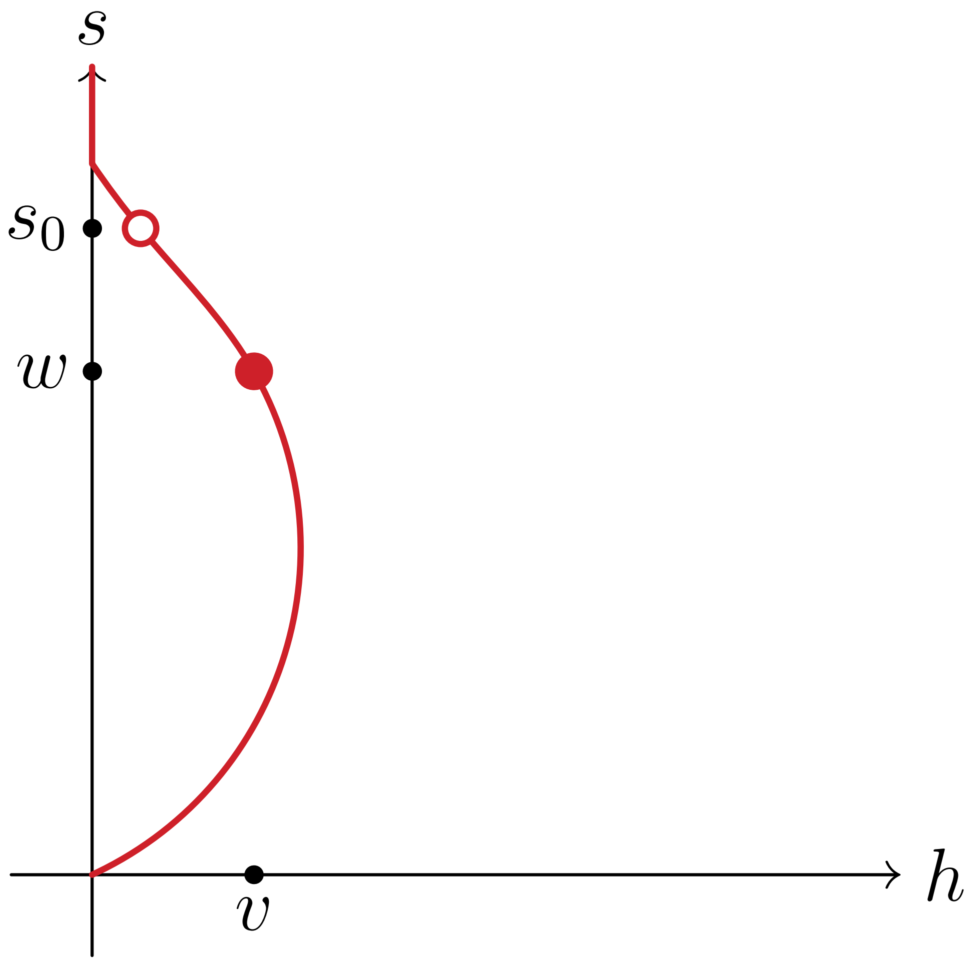
$$\theta \approx \sqrt{-\frac{\beta^3_{\lambda_{HS}}\ln R}{2\lambda_H}}\,\frac{1+\ln R}{4\pi(2\beta_{\lambda_S}+\beta_{\lambda_{HS}}\ln R)},$$

β-function suppressed

For small couplings the CW must be treated with better precision than the Gildener-Weinberg approximation

The origin of the effect

- Arrange tree-level Gildener-Weinberg flat direction along the s-axis
- Quantum effects bend the flat direction to a banana
- Usually this is just neglected small effect
- Due to the multi-phase criticality, the EW scale is loop suppressed



Comments

- In realistic models couplings never run to zero at the same scale:

$$\lambda_S(\bar{\mu}) = 0, \qquad \lambda_{HS}(\bar{\mu}) \approx 0$$

- Small quartic couplings from pheno:
  - Higgs $\lambda(10^{10}\text{GeV}) = 0$, inflaton $\lambda < 10^{-12}$, DM freeze-in requires $\lambda \ll 1$
  - Triviality?

- Top Yukawa affects perpendicular direction of the flat direction

- In realistic models one need more scalar couplings to have dynamical symmetry breaking along the multi-phase criticality direction

DM induced dynamical symmetry breaking

Assume freeze-out of DM

DM induced multi-critical dynamical symmetry breaking

- The scalar model: the Higgs, a dilaton and scalar DM

$$V = \lambda_H |H|^4 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{S'}}{4} S'^4 + \frac{\lambda_{HS}}{2} |H|^2 S^2 + \frac{\lambda_{HS'}}{2} |H|^2 S'^2 + \frac{\lambda_{SS'}}{4} S^2 S'^2.$$

$$m_h^2 \simeq -\frac{\beta_{\lambda_{HS}}}{(4\pi)^2} w^2 \ln R,$$

$$m_s^2 \simeq 2 \frac{\beta_{\lambda_S}}{(4\pi)^2} w^2,$$

$$m_{s'}^2 \simeq \frac{1}{2} \lambda_{SS'} w^2.$$

$$\lambda_{SS'} \approx \frac{(4\pi)^2 m_s^2}{m_{s'}^2},$$

$$\lambda_{HS'} \approx -\frac{(4\pi)^2 m_h^2}{m_{s'}^2 \ln R}.$$

$$\theta \simeq \frac{2\sqrt{2}\pi m_s m_h^2 v (1 + \ln R)}{(m_h^2 - m_s^2) m_{s'}^2 \ln R}.$$

$$w \simeq \frac{\sqrt{2} m_{s'}^2}{4\pi m_s}.$$

One scale w

Scalar DM must be heavy, the dilaton can be heavier or lighter than the Higgs boson

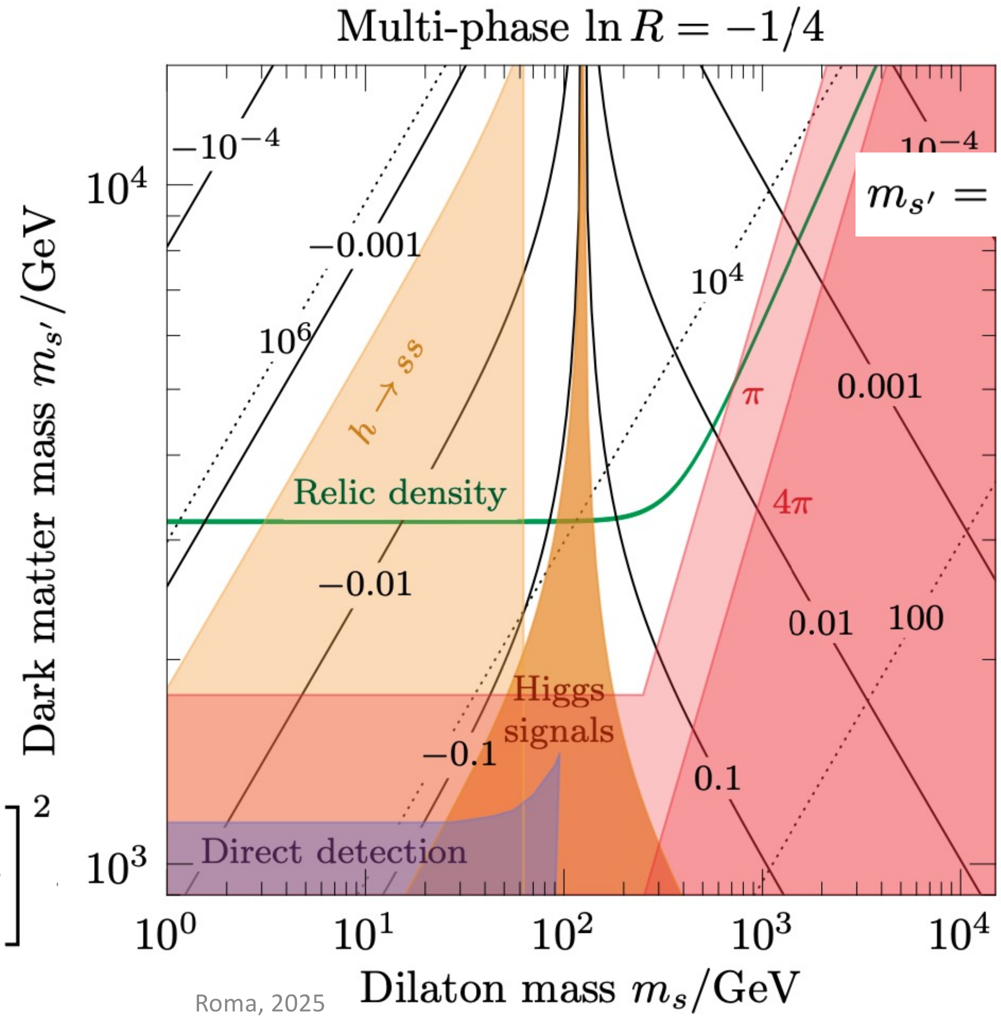
DM freeze out in this model

$$\sigma_{\rm ann} v_{\rm rel} \approx \frac{\lambda_{SS'}^2 + 4\lambda_{HS'}^2}{64\pi m_{s'}^2}$$

$$\sigma_{\rm ann} v_{\rm rel} \approx \frac{1}{M^2}$$

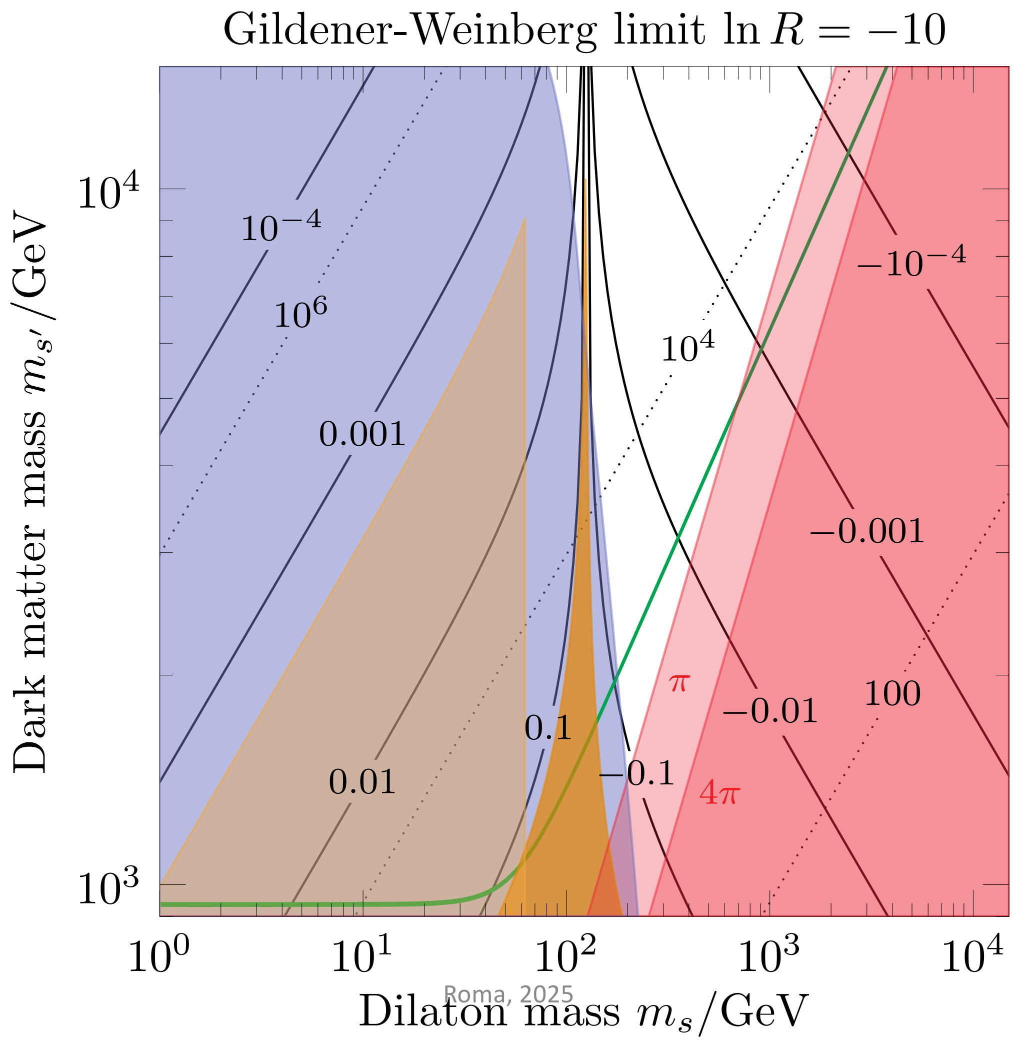
$$m_{s'} = \sqrt{\pi}(2m_h)^{2/3} M^{1/3}/(-\ln R)^{1/3}$$

$$\sigma_{\rm SI} \simeq \frac{f_N^2 m_N^4}{4\pi m_{s'}^2}\left[\frac{\lambda_{HS'}}{m_h^2} + \frac{\lambda_{SS'}}{m_s^2}\frac{1+\ln R}{\ln R}\right]^2$$



$$m_{s'} = \sqrt{\pi} m_s^{2/3}(2M)^{1/3}$$

DM freeze-out in the Gildener-Weinberg limit



To motivate the small scalar couplings:

repeat everything for freeze-in of DM

DM freeze-in in the multi-critical framework

- All scalar couplings, except the Higgs quartic, must be super small

- Criticality naturally embedded: $\lambda_S(\bar{\mu}) = 0, \qquad \lambda_{HS}(\bar{\mu}) \approx 0$

- Introduce RH neutrinos N (Seesaw Type I)

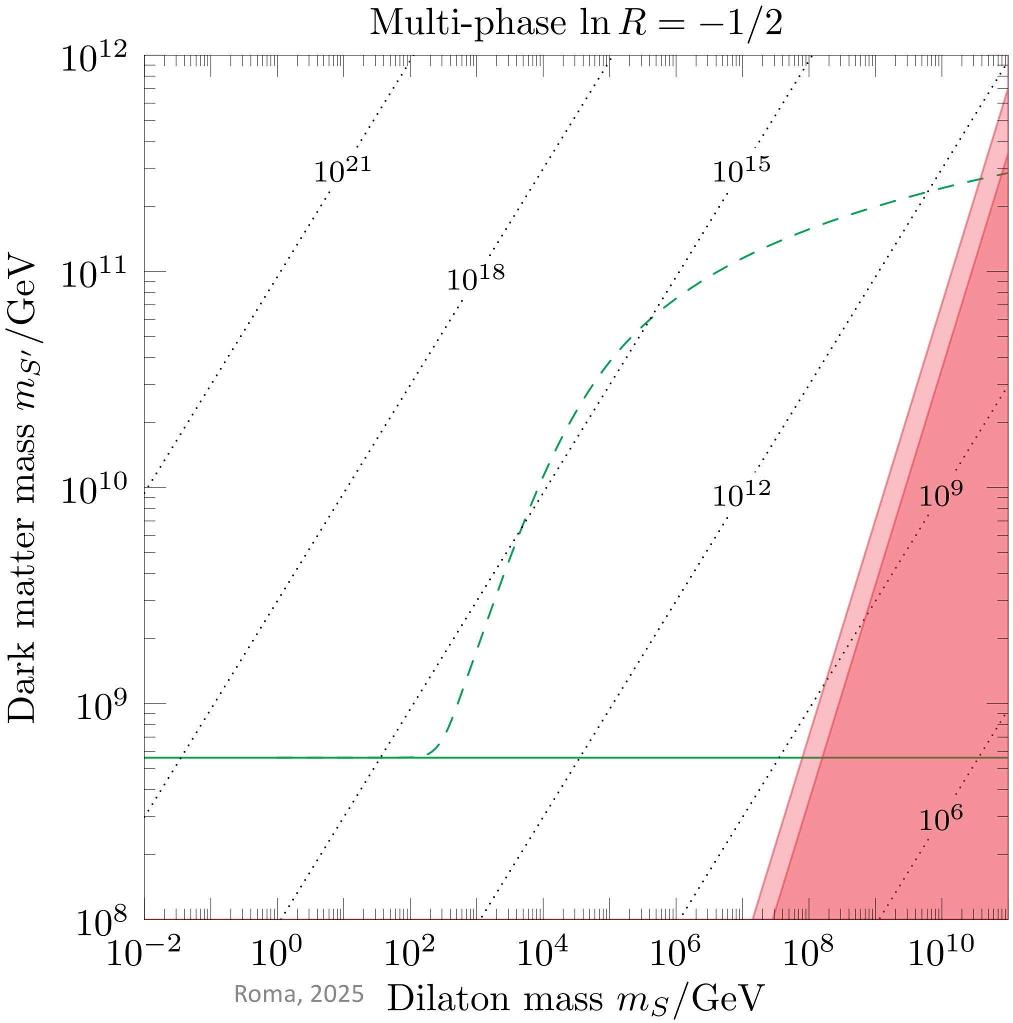
$$-\mathcal{L}_Y = y_H \bar{\ell} \tilde{H} N_R + \frac{y_S}{2} S \bar{N}_R^c N_R + \text{h.c.},$$

- Neutrino masses and leptogenesis coming from the same framework

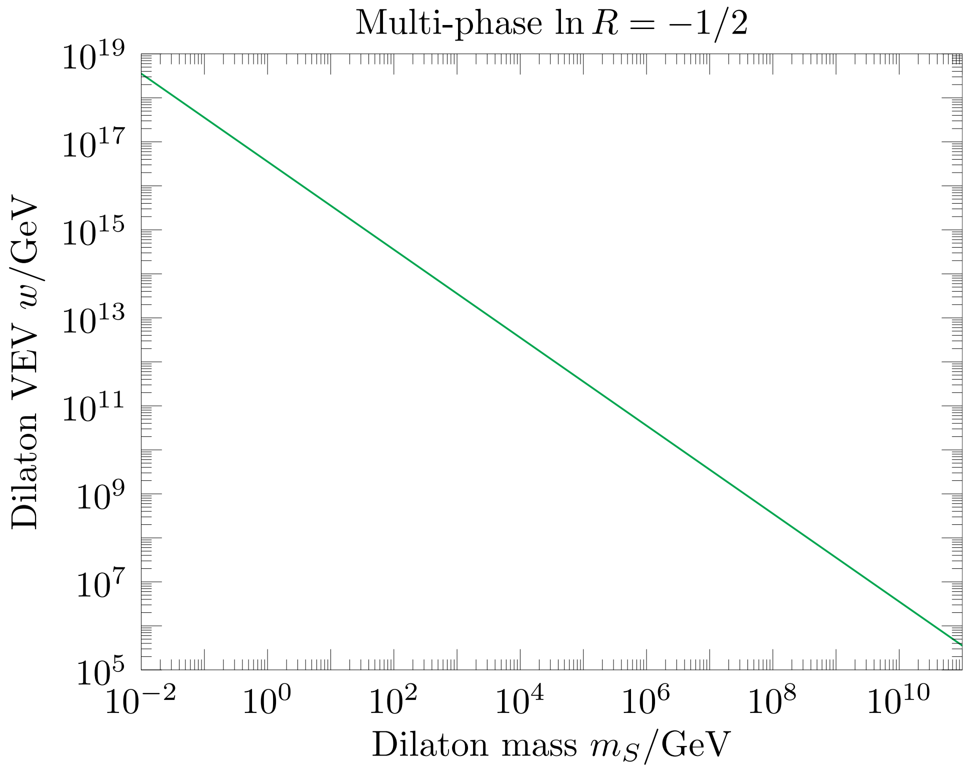
DM induced CW and freeze-in results

$$v_{\rm rel}\sigma_{S'S'\to XX} \simeq \frac{4\lambda_{HS'}^2+\lambda_{SS'}^2}{16\pi s}\,.$$

Dilaton never thermalizes



DM induced hierarchy in scales



m_S/GeV	$m_{S'}$/GeV	w/GeV	λ_S	λ_{HS}	$\lambda_{HS'}$	$\lambda_{SS'}$
10	5.62×10^8	3.55×10^{15}	-1.98×10^{-30}	-2.48×10^{-27}	1.57×10^{-11}	5.00×10^{-14}
10^4	5.62×10^8	3.55×10^{12}	-1.98×10^{-18}	-2.48×10^{-9}	1.56×10^{-11}	5.00×10^{-8}

Comments

- This models induces all the known scales in particle physics
  - There is one dynamical symmetry breaking scale w

    10^9 GeV < w < 10^{18} GeV
  - The DM and the RH neutrino mases, $m^2_{DM} \sim \lambda_{SS} w^2 \sim 10^9$ GeV, $M_N = y_N w$
  - The SM particle masses, $m_e = y_e$ v, $m_t = y_t$ v, where $v \sim \beta w$
  - The light neutrino masses come from the seesaw, $m_{\nu 1} = y^2_H / M_N$ v^2
  - Standard leptogenesis from Majorana N decays
- The model is technically natural – the effective potential is stable
- No hierarchy problem
- The model has two predictions:
  1. The existence of a new particle - the dilaton with preferably small mass
  2. The DM is a scalar with a fixed mass 5.6 10^8 GeV

Renormalization of scalars after the LHC

Standard folklore

- Assume NP separate from the SM
- Use the EFT framework to claim

$$\delta m_h^2 \sim y_t^2/(4\pi)^2\Lambda_{\rm NP}^2$$

- Misuse of the ETF framework and non-physical bare parameters

Shaposhnikov et al

- Consider the full system
- Only physical parameters matter
- Once the physical parameters are fixed, only log running remains
- The hierarchy problem is a problem of giving physical significance to bare parameters

Possible extensions of the framework

- Add non-minimal coupling to gravity

$$-\frac{1}{2}\xi R s^2 \quad \rightarrow \quad M^2{}_{PL} = \xi w^2$$

- Add extra scalars or extra non-minimal couplings for inflaton

Conclusions

- The simplest scalar model containing H, S, S’ with one high scale w

$$w > M_{NR} \sim M_{DM} >> v >> m_{\nu}$$

- The scalar DM couplings trigger the CW and the loop-suppressed EW scale
- Huge but technically natural hierarchy between the EW and DM scales
- Neutrino masses and leptogenesis occur in a standard way ($M_{NR} \sim M_{DM}$)
- This scenario predicts:
  - A light scalar, the dilaton, which may be lighter or heavier than the SM Higgs boson
  - The scalar DM with a fixed mass $5.6\ 10^{8}$ GeV