The origin of scales in particle physics

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2102.01084 [hep-ph]
2201.00824 [hep-ph]
2204.01744 [hep-ph]
Work in progress

Outline

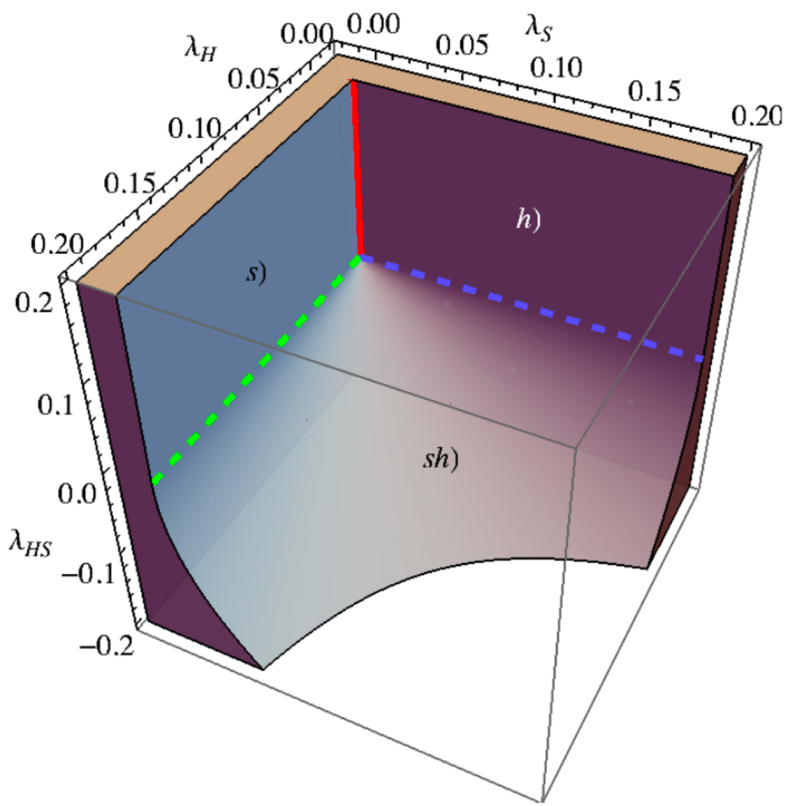
Aim: Explain hierarchies in physical scales (absence of NP at the LHC)

- 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
- The most minimal scalar DM model of dynamical symmetry breaking

There is only one, HIGH scale for all particle physics

The hierarchies in physical phenomena come 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

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

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

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

***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**

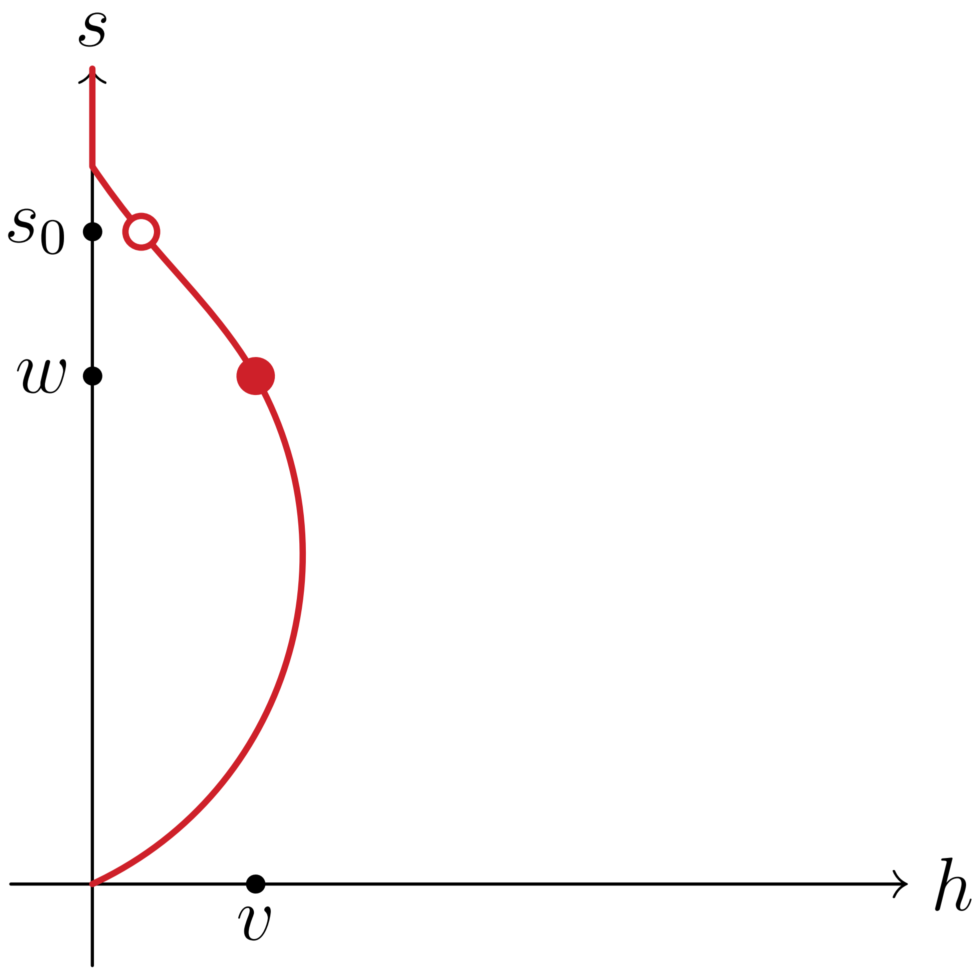
$$\theta \approx \sqrt{-\frac{\beta^3_{\lambda_{HS}}\ln R}{2\lambda_H}}\frac{1+\ln R}{4\pi(2\beta_{\lambda_S}+\beta_{\lambda_{HS}}\ln R)},$$

***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: inflaton λ<10^{-12}, Higgs λ(10^{10}GeV), freeze-in

- 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

The most minimal realistic scalar DM+CW model

Assume freeze-out of DM

DM induced multi-critical dynamical symmetry breaking

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

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

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

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

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

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

One scale w

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

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

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

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

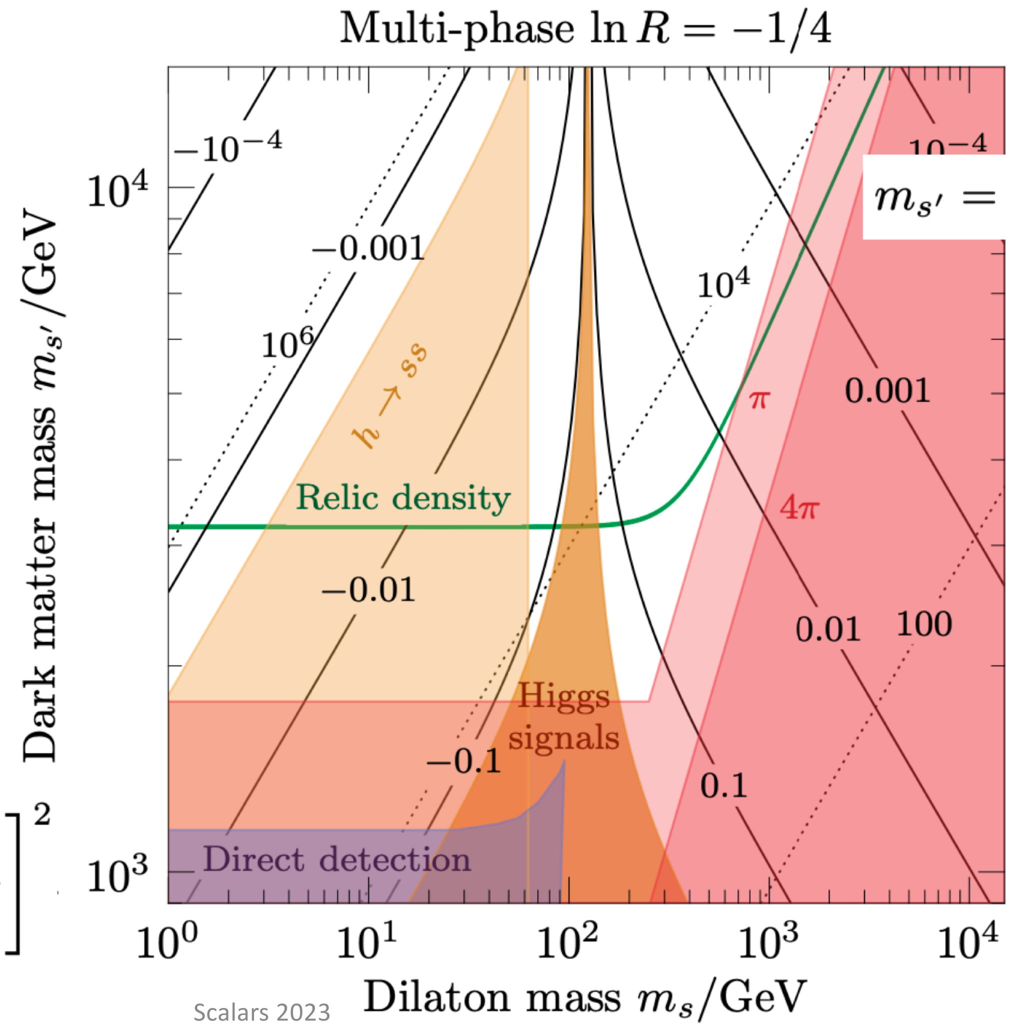
DM freeze out in this model

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

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

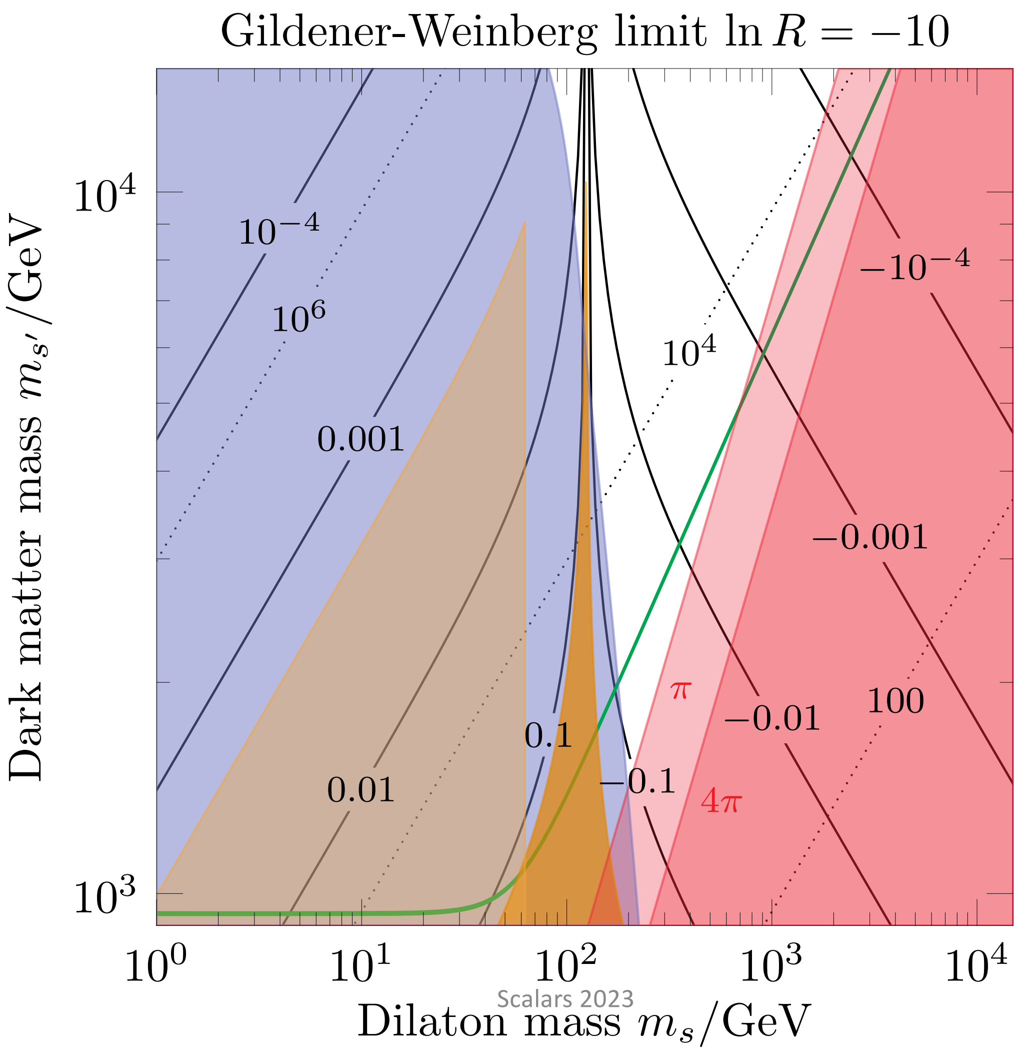
$$m_{s'} = \sqrt{\pi}(2m_h)^{2/3} M^{1/3}/(-\ln R)^{1/3}$$

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



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

DM freeze out in the Gildener-Weinberg limit



Assume 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: $\lambda_S(\bar{\mu}) = 0, \qquad \lambda_{HS}(\bar{\mu}) \approx 0$
- A possibility: introduce RH neutrinos N (Seesaw Type I)

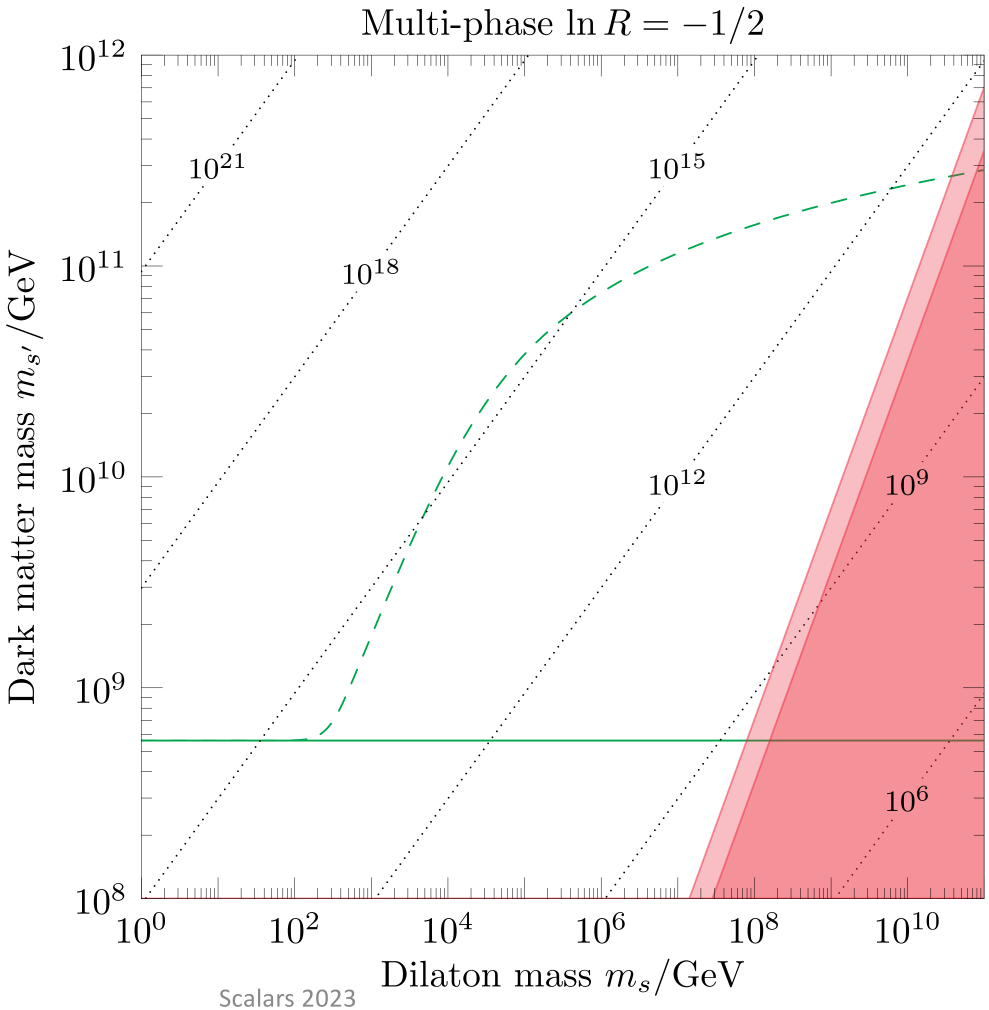
$$-\mathcal{L}_Y = y_H \bar{\ell} \tilde{H} N_R + \frac{y_S}{2} S \bar{N}_R^c N_R + \text{h.c.},$$

- Neutrino masses and leptogenesis coming from the same framework

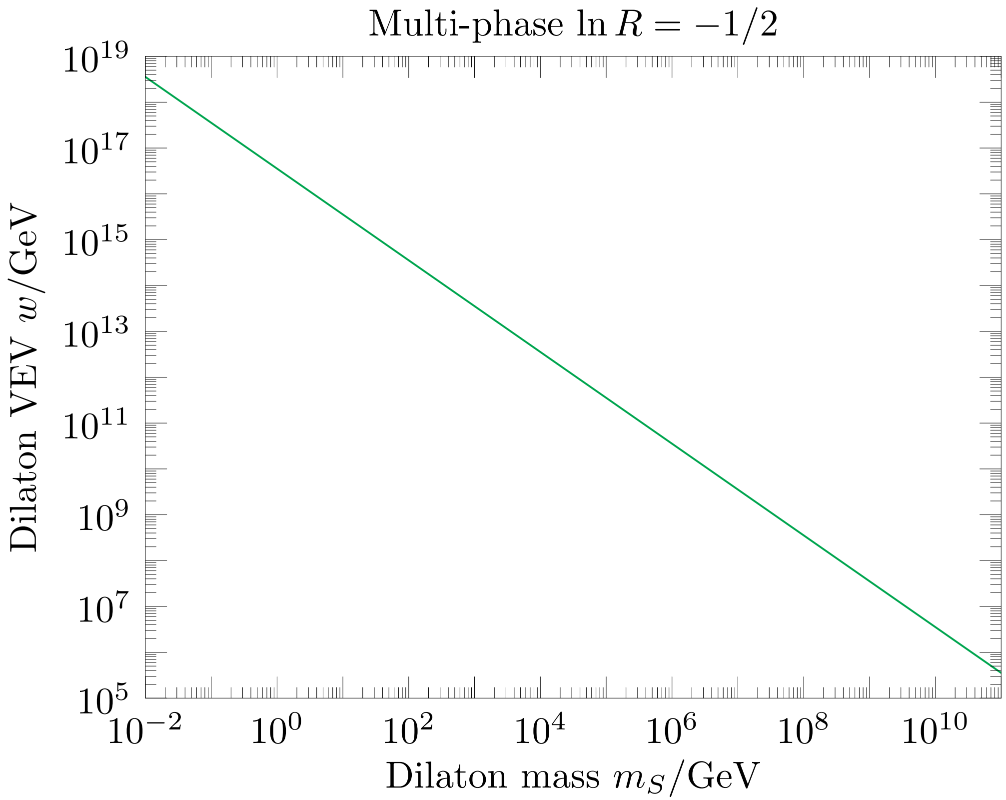
DM induced CW and freeze-in results

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

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}

Conclusions

- The simplest scalar model containing H, S, S' with one high scale w from dynamical SB

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

- 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 one more light scalar, the dilaton, which may be lighter or heavier than the SM Higgs boson.