Multi-phase criticality

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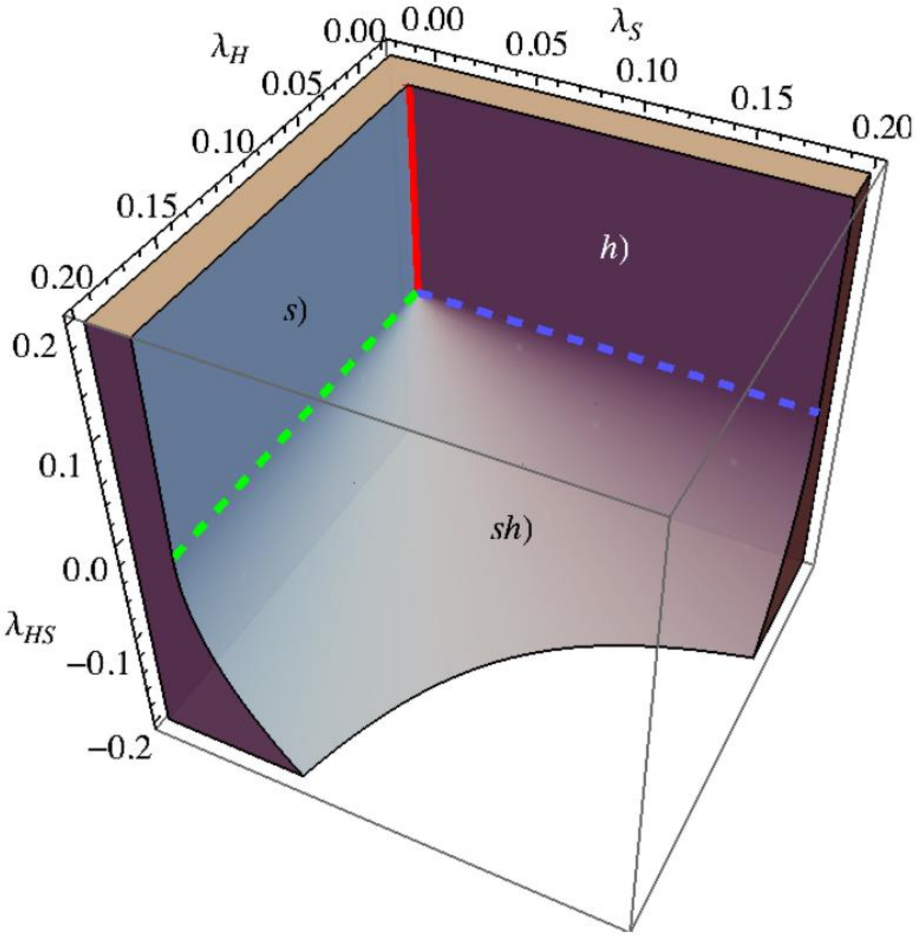
Work in progress

Outline

Explain hierarchies in physics scales (absence of NP at the LHC) with:

- Multi-phase criticality and Coleman-Weinberg mechanism
- Freeze-out in DM induced multi-phase dynamical symmetry breaking
- Freeze-in in DM induced multi-phase dynamical symmetry breaking
- Conclusions

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 $s)\ s \neq 0 \text{ and } h = 0$

$$\lambda_S = 0$$

- Phase $h)\ h \neq 0 \text{ and } s = 0$

- 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

$$V^{(1)}|_{\overline{\rm MS}} = \frac{1}{4(4\pi)^2}\,{\rm Tr}\left[M_S^4\left(\ln\frac{M_S^2}{\bar\mu^2}-\frac{3}{2}\right)+\right.$$

$$\left.-2M_F^4\left(\ln\frac{M_F^2}{\bar\mu^2}-\frac{3}{2}\right)+3M_V^4\left(\ln\frac{M_V^2}{\bar\mu^2}-\frac{5}{6}\right)\right] \quad (10)$$

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

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

$\boldsymbol{\beta}$-function suppressed

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

$\boldsymbol{\beta}$-function suppressed

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

$\boldsymbol{\beta}$-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 $\lambda<10^{-12}$, Higgs $\lambda(10^{10}\mathrm{GeV})$, 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

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

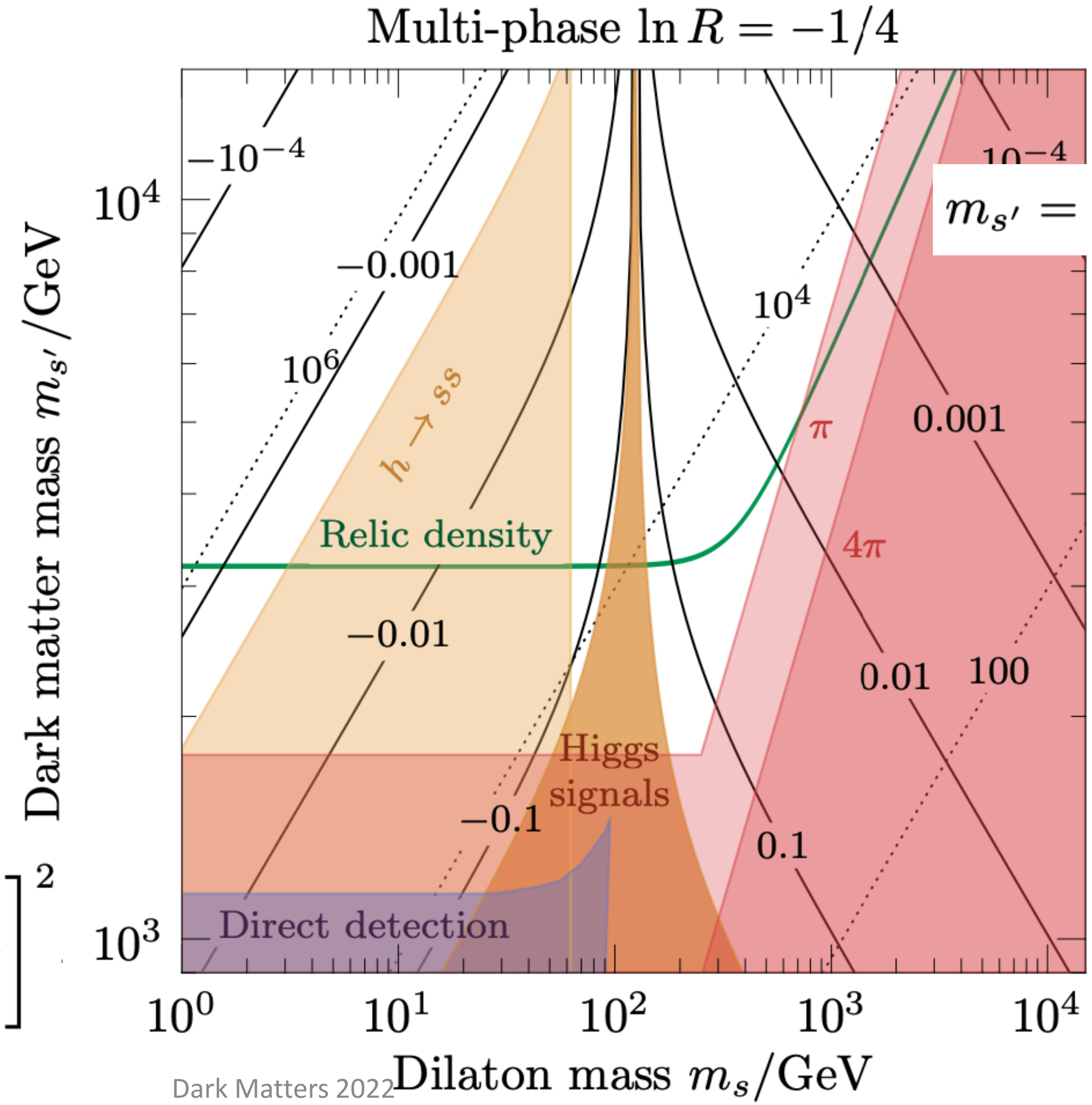
DM freeze out in this model

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

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

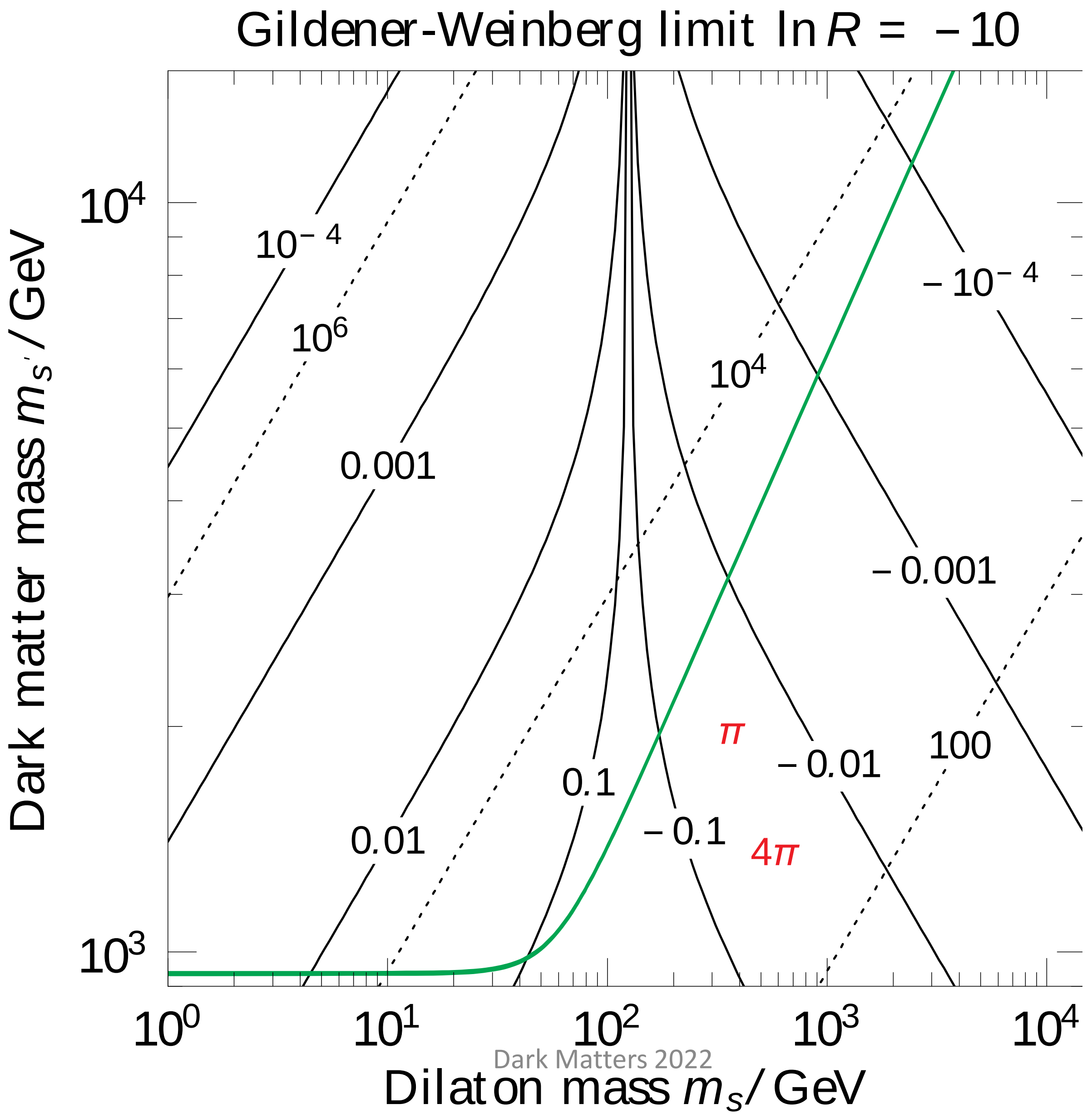
$$m_{s'} = \sqrt{\pi}(2m_h)^{2/3} M^{1/3}/(-\ln R)^{1/3}$$

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



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

DM freeze out in the Gildener-Weinberg limit



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

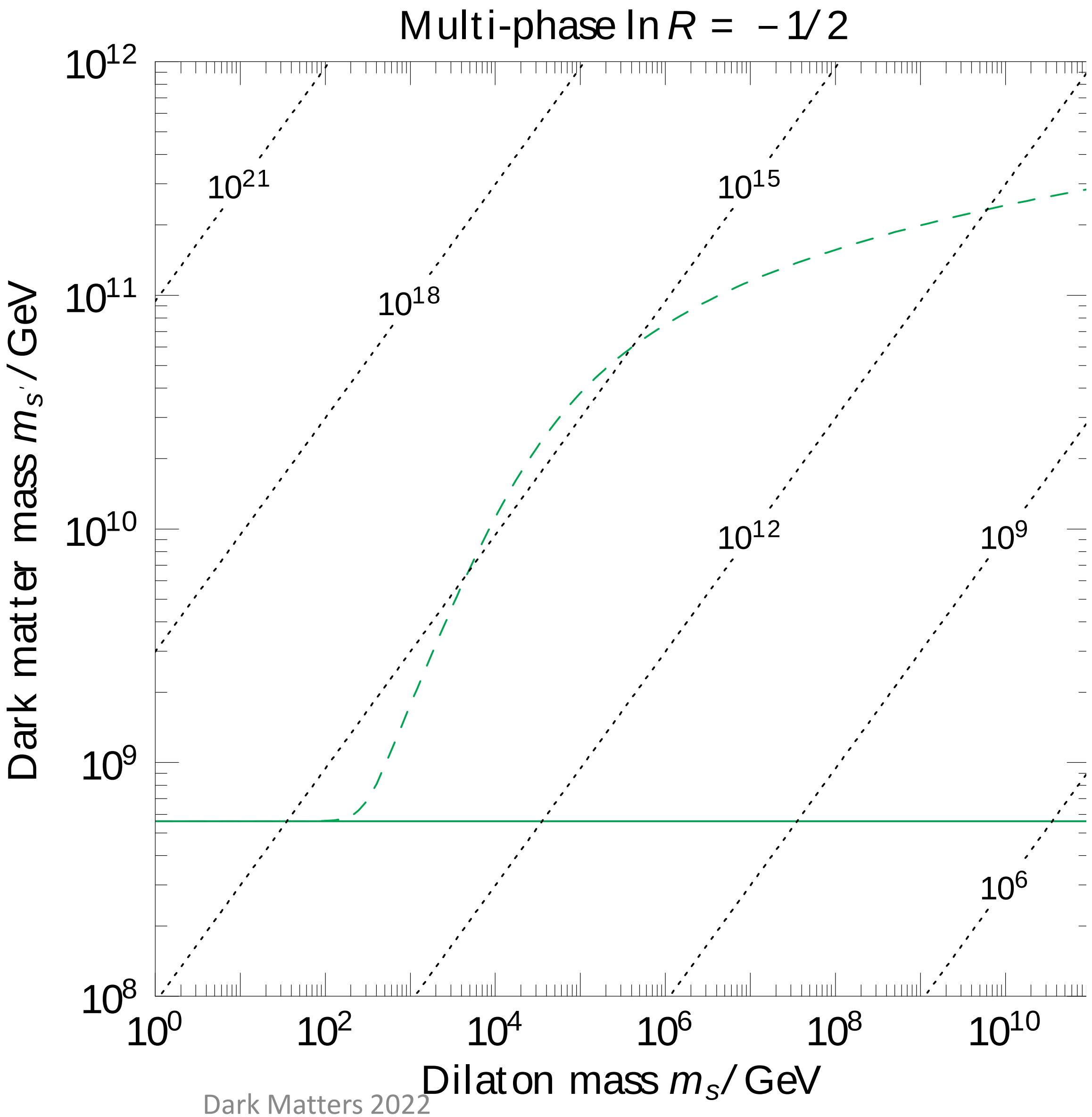
$$-\mathcal{L}_Y = y_H \bar{\ell} \tilde{H} N_R + \frac{y_S}{2} S \bar{N}_R^c N_R + \text{h.c.},$$

- Neutrino masses and leptogenesis coming from the same framework

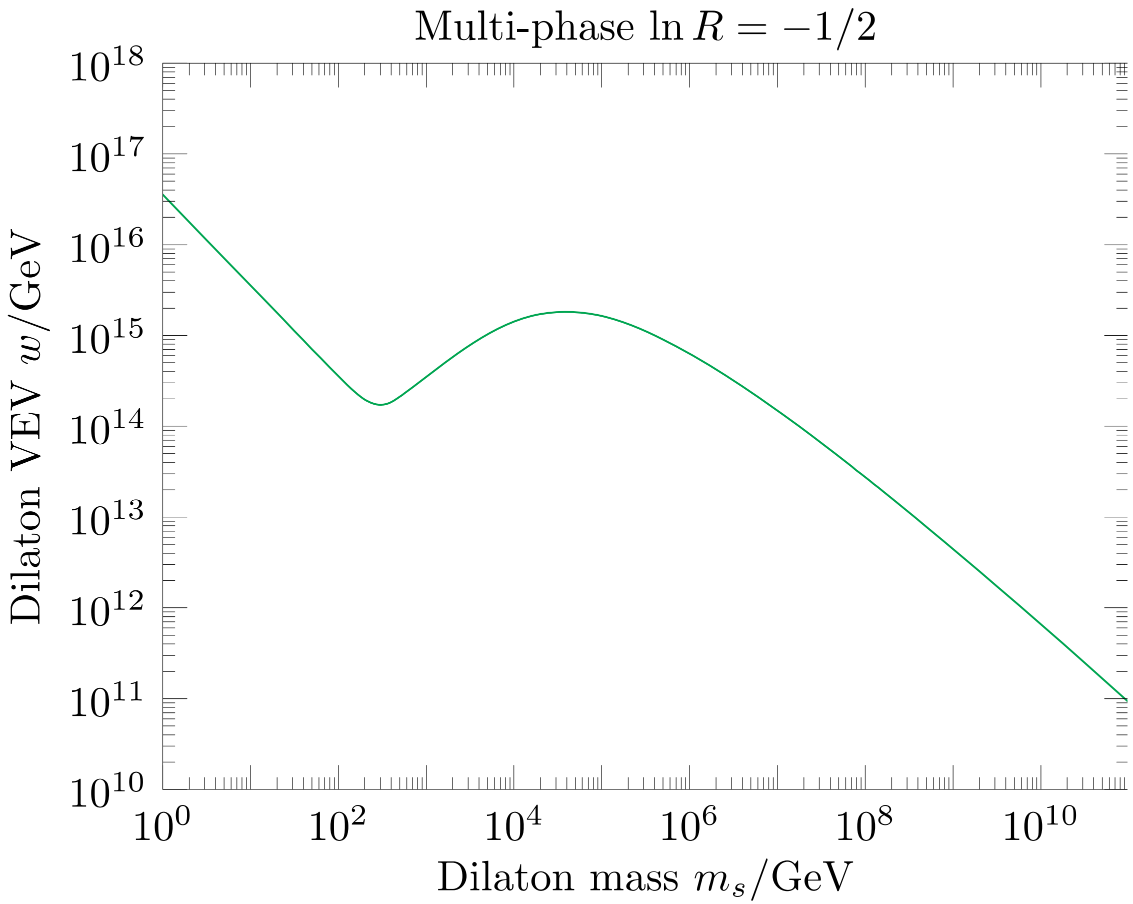
DM induced CW and freeze-in results

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

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

- Multi-phase criticality combines "small" and "large" scalar couplings
- The scalar DM is heavy, it triggers the CW and the loop-suppressed EW scale
- Huge but technically natural hierarchy between the EW and DM scales
- Neutrino masses and leptogenesis may be obtained in a standard way
- This scenario predicts one more light scalar, the dilaton, which may be lighter or heavier than the SM Higgs boson.