Multi-Phase Dynamical Symmetry Breaking by Scalar Dark Matter

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Martti Raidal, Alessandro Strumia & Venno Vipp

Phys.Lett.B 832 (2022) 137214 [arXiv:2204.01744]

Moriond EW 2023 ✧ La Thuile

2 Motivation

- Dynamical symmetry breaking can relieve the hierarchy problem
- Near the critical phase boundary both dilaton and Higgs can be light
- Quantum corrections driven by couplings to dark matter
- Model to explain (almost) everything

  Ishiwata, Phys. Lett. B 710 (2012) 134–138 [arXiv:1112.2696]

  Gabrielli, Heikinheimo, K.K, Racioppi, Raidal, Spethmann, Phys. Rev. D 89 (1) (2014) 015017 [arXiv: 1309.6632]

  Kang, Zhu, Phys. Rev. D 102 (5) (2020) 053011 [arXiv:2003.02465]

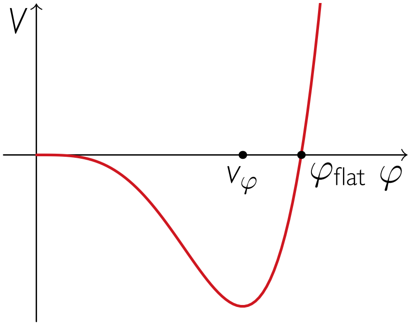
3 Mechanism

- Multi-phase dynamical symmetry breaking
  K.K., Luca Marzola, Martti Raidal, Alessandro Strumia
  Phys.Lett.B 816 (2021) 136241 [arXiv:2102.01084]
- Model-independent collider phenomenology
  Katri Huitu, K.K., Niko Koivunen, Luca Marzola,
  Subhadeep Mondal, Martti Raidal
  Phys.Rev.D 105 (2022) 9, 095036 [arXiv:2201.00824]
- **Dark-matter-driven symmetry breaking**
  K.K., Niko Koivunen, Aleksei Kubarski, Luca Marzola,
  Martti Raidal, Alessandro Strumia & Venno Vipp

  Phys.Lett.B 832 (2022) 137214 [arXiv:2204.01744]

4 Dynamical Symmetry Breaking

- No dimensionful terms in the scalar potential
- Symmetry broken by quantum corrections via the Coleman-Weinberg mechanism
- Minimum near the flat direction $V(\mu_{\text{flat}}) = 0$



S. R. Coleman, E. J. Weinberg, Phys. Rev. D 7 (1973) 1888–1910

E. Gildener, S. Weinberg, Phys. Rev. D 13 (1976) 3333

5 Model with Scalar Dark Matter

Tree-level scalar potential given by

$$V = \frac{1}{4}\lambda_H h^4 + \frac{1}{4}\lambda_S s^4 + \frac{1}{4}\lambda_{HS} h^2 s^2 + \frac{1}{4}\lambda_{HS'} h^2 s'^2 + \frac{1}{4}\lambda_{SS'} s^2 s'^2 + \frac{1}{4}\lambda_{S'} s'^4$$

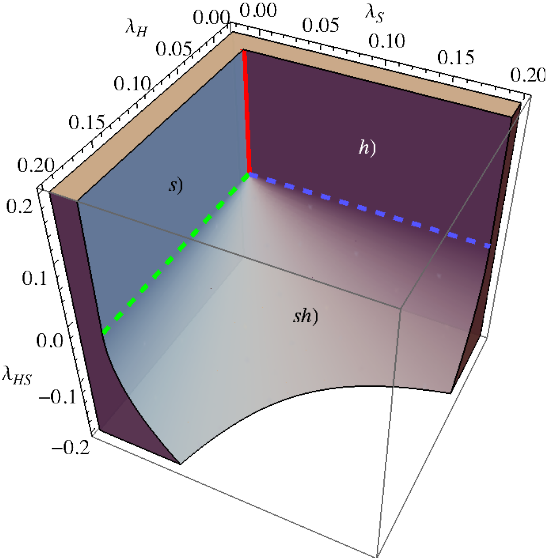
- In addition to the Higgs boson h, dilaton s, and dark matter s'
- Invariant under a $\mathbb{Z}_2 \otimes \mathbb{Z}_2'$ with $s \to -s$ and $s' \to -s'$
- VEVs $\langle h \rangle \equiv v$ and $\langle s \rangle \equiv w$

6 Phases: Higgs & Dilaton

h) $\lambda_H = 0$ and
$\lambda_S, \lambda_{HS} > 0$ for
non-zero v

s) $\lambda_S = 0$ and
$\lambda_H, \lambda_{HS} > 0$ for
non-zero w

sh) $\lambda_{HS} = -2\sqrt{\lambda_H \lambda_S} < 0$
and $\lambda_H, \lambda_S > 0$
for both v and w
non-zero



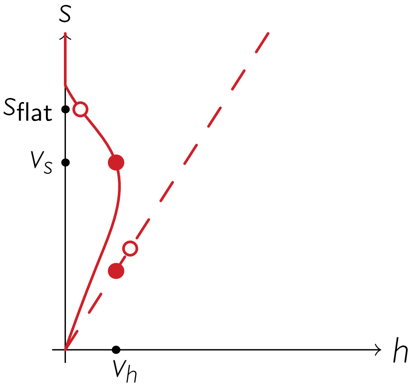
7 Two Regimes

- In the Gildener-Weinberg regime, $\lambda_{HS}(w) \approx \lambda_{HS}(s_{\text{flat}})$ and

$$\frac{v}{w} \approx \sqrt{\frac{-\lambda_{HS}(s_{\text{flat}})}{2\lambda_H}}$$

- In the multi-phase critical regime, $\lambda_S(s_{\text{flat}}) \approx 0$, $\lambda_{HS}(w) \ll \lambda_{HS}(s_{\text{flat}}) \approx 0$, s and sh phases coincide and the Gildener-Weinberg approximation breaks down

Two Regimes



⚠ Angles not drawn to scale

9 Quantum Corrections

- RGE running driven by couplings to dark matter
- In the critical limit, the single dominant mass scale is

$$m_{S'}^2 = \frac{1}{2}(\lambda_{SS'}s^2 + \lambda_{HS'}h^2)$$

- For $\lambda_S \approx 0$ and $\lambda_{HS} \approx 0$, β-functions given by

$$\beta_{\lambda_{HS}} \approx \frac{1}{2}\lambda_{SS'}\lambda_{HS'}, \qquad \beta_{\lambda_S} \approx \frac{1}{4}\lambda_{SS'}^2$$

- Dark matter Higgs portal $\lambda_{HS'}$ important for symmetry breaking *and* direct detection

10 Quantum Corrections

Effective potential

$$V_{\text{eff}} = V^{(0)} + V^{(1)} \approx V^{(0)}(\lambda_i(\mu = s))$$

Running couplings parametrised as

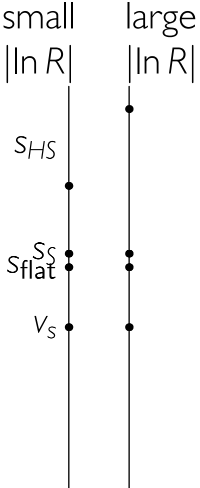
$$\lambda_S^{\text{eff}}(s) = \frac{\beta_{\lambda_S}}{(4\pi)^2} \ln \frac{s^2}{s_S^2},$$

$$\lambda_{HS}^{\text{eff}}(s) = \frac{\beta_{\lambda_{HS}}}{(4\pi)^2} \ln \frac{s^2}{s_{HS}^2}$$

$$= \frac{\beta_{\lambda_{HS}}}{(4\pi)^2} \ln \frac{R\, s^2}{e^{-1/2} s_S^2}$$

- The ratio

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



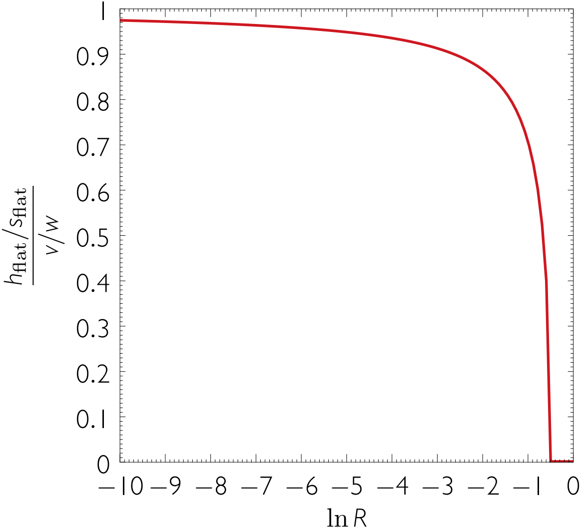
Quantum Corrections

- Flat direction scale $s_{\text{flat}} \approx s_S$
- Dilaton VEV $w \approx s_S\, e^{-1/4}$
- Higgs VEV

$$v = \frac{w}{4\pi}\sqrt{-\frac{\beta_{\lambda_{HS}} \ln R}{2\lambda_H}}$$

suppressed by quantum corrections

Quantum Corrections



$$\sqrt{\frac{\lambda^{\rm eff}_{HS}(s_{\rm flat})}{\lambda^{\rm eff}_{HS}(w)}} = \frac{h_{\rm flat}}{s_{\rm flat}} \Big/ \frac{v}{w} = \sqrt{1+\frac{1}{2\ln R}} \quad \text{if } \ln R < -\frac{1}{2}$$

Parameters

- Higgs mass $m_h \approx \sqrt{2\lambda_H} v \approx 125.1$ GeV
- Higgs VEV $v = 246.2$ GeV
- Free parameters: m_s, $m_{s'}$, $\ln R$
- Dark matter self-coupling $\lambda_{S'}$ largely irrelevant (not too large)
- Loop-level $m_s^2 \propto \beta_{\lambda_S}$, $m_h^2 \propto \beta_{\lambda_{HS}}$, tree-level $m_{s'}^2 \propto \lambda_{SS'}$

14 Parameters

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

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

$$w \approx \frac{\sqrt{2} m_{s'}^2}{4\pi\, m_s}$$

and

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

Dark Matter Abundance

- $\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$

  N. Aghanim, et al., Astron. Astrophys. 641 (2020) A6

- Heavy-DM limit $m_{s'} \gg m_s, m_h$, where the non-relativistic DM annihilation cross section is simply given by

$$\sigma_{\rm ann} v_{\rm rel} \approx \frac{\lambda_{SS'}^2 + 4\lambda_{HS'}^2}{64\pi m_{s'}^2} \approx 4\pi^3 \frac{m_s^4 + 4m_h^4/\ln^2 R}{m_{s'}^6}$$

- Higgs-dominated for $m_s \ll m_h$, dilaton-dominated for $m_s \gg m_h$

Direct Detection

Effective coupling to nucleons

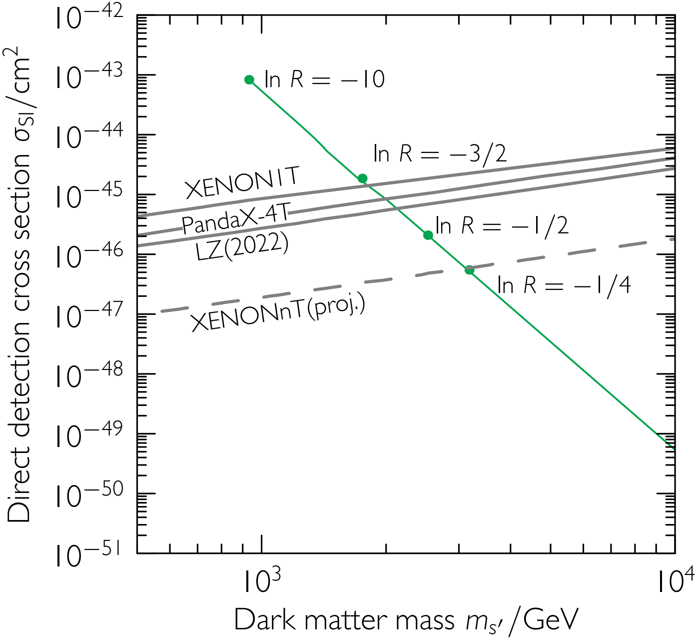
$$\frac{f_N m_N}{v} h\bar{N}N,$$

gives

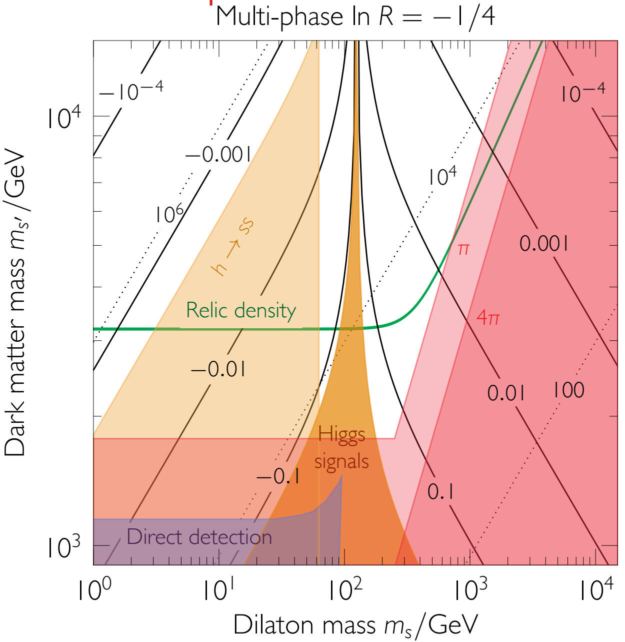
$$\sigma_{SI} \approx \frac{64\pi^3 f_N^2 m_N^4}{m_{s'}^6},$$

where $m_N = 0.946$ GeV
is the nucleon mass and $f_N \approx 0.3$

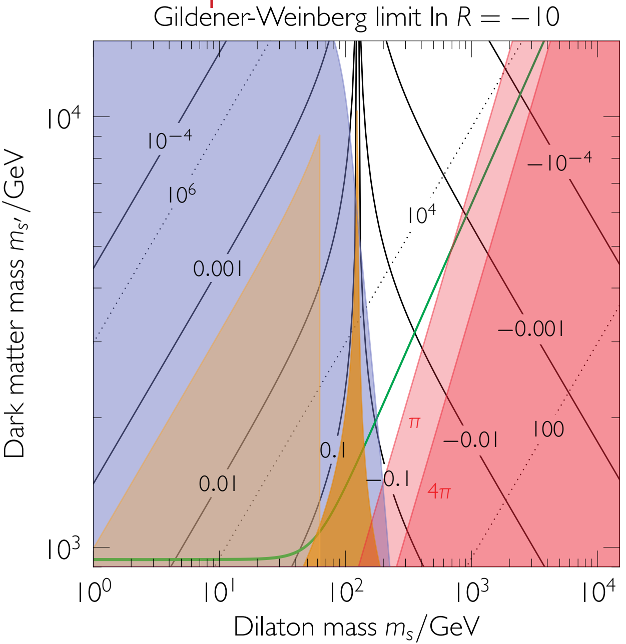
Direct Detection



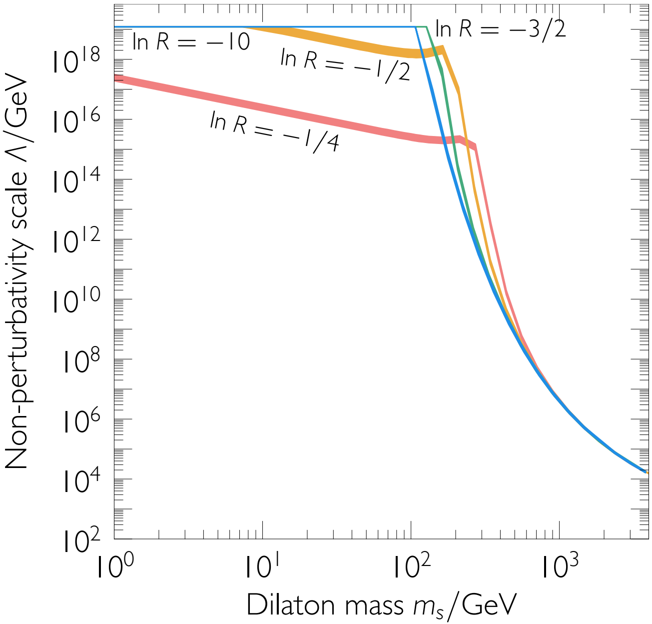
18 Parameter Space



Parameter Space



20 Perturbativity



Completing the Model

- Type-I seesaw mechanism with right-handed neutrinos N_R
- Yukawa Lagrangian

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

where $\tilde{H} \equiv i\tau_2 H^*$

- Light enough neutrinos do not ruin the mechanism
- Can do leptogenesis
- Inflation with the dilaton s

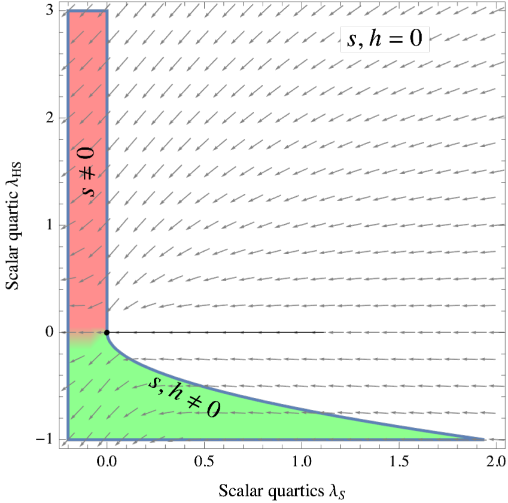
Brief on Freeze-In

- Dark matter mass $m_{S'} \sim 10^8$ GeV
- Tiny couplings: for $m_S = 10$ GeV,
  $\lambda_{SS'} \sim 10^{-11}$, $\lambda_{HS'} \sim 10^{-14}$,
  $\lambda_S \sim 10^{-30}$, $\lambda_{HS} \sim 10^{-27}$
- One large scale that gives rise to other scales
- Impossible to detect at accessible energies
  (except dilaton-Higgs mixing)

Conclusions

- One scale to rule them all:
  dynamical symmetry breaking
  driven by couplings to dark matter
- Crucial corrections to Gildener-Weinberg
  approximation in the multi-phase critical regime
- Both dilaton and Higgs mass loop-suppressed
- Clear prediction for direct detection
- Inflation & leptogenesis
  with heavy right-handed neutrinos

RGE Flow Attractor



- Starting from $\lambda_S \gg \lambda_{HS} \gg 1$
- Takes $(4\pi)^2$ orders of magnitude…

Parameters

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

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

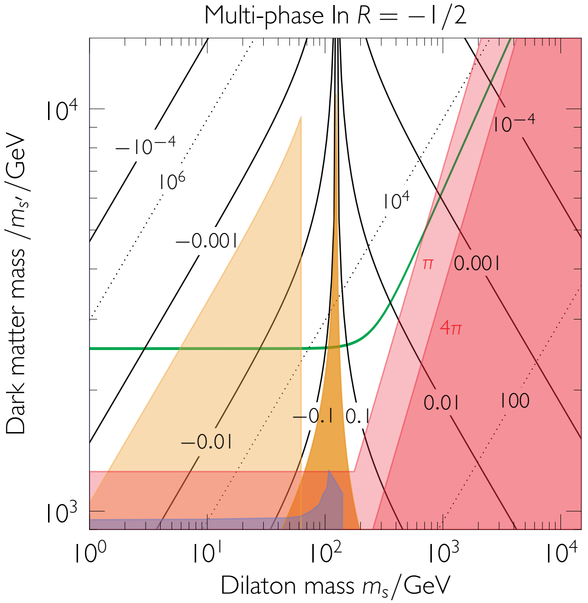
$$m_{s'}^2 \approx \frac{1}{2}\lambda_{SS'} w^2,$$

while the mixing angle is given by

$$\theta \approx \frac{m_{hs}^2}{m_s^2 - m_h^2} = \frac{\beta_{\lambda_{HS}}(1 + \ln R)}{2\beta_{\lambda_S} + \beta_{\lambda_{HS}} \ln R} \frac{v}{w},$$

where m_{hs}^2 is the mixing mass term among h and s

26 Parameter Space



Parameter Space