Multi-Phase Dynamical Symmetry Breaking by Scalar Dark Matter

Kristjan Kannike

NICPB, Estonia

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2 Motivation

- Classical scale invariance can relieve the hierarchy problem
- Both dilaton and Higgs can be light near the critical phase boundary
- Quantum corrections driven by couplings to dark matter

3 Works

- 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

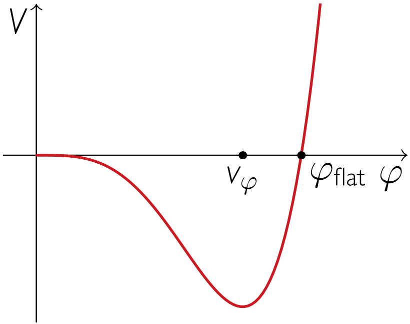
  Phys.Rev.D 105 (2022) 9, 095036 [arXiv:2201.00824]

- Scalar singlet dark matter
  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
- Classical scale invariance broken by quantum corrections
- Minimum near the flat direction ($V = 0$)



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

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 $\langle s \rangle \equiv w$
- Sufficient to require $\lambda_{S'}, \lambda_{HS'}, \lambda_{SS'} > 0$ to avoid a VEV for dark matter s'

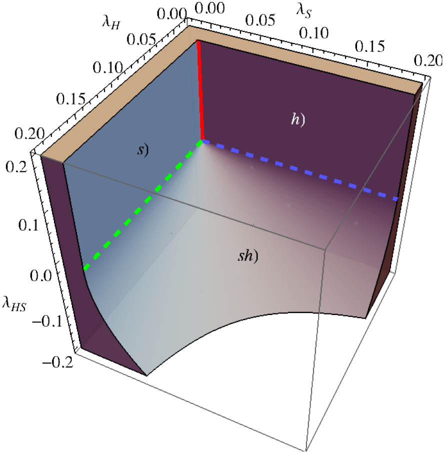
6 Phases

Symmetry is broken dynamically when
a combination of quartics runs through zero

h) $\lambda_H = 0$ and $\lambda_S, \lambda_{HS} > 0$
for $v \neq 0$ and $w = 0$

s) $\lambda_S = 0$ and $\lambda_H, \lambda_{HS} > 0$
for $w \neq 0$ and $v = 0$

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



7 Phases

- The *sh* phase gives,
  in the Gildener-Weinberg approximation,

$$\frac{v}{w} = \sqrt{\frac{-\lambda_{HS}}{2\lambda_H}}$$

- Gildener-Weinberg approximation breaks down in the critical regime
  where the *s* and *sh* phases coincide
- Better approximation takes into account running between the flat direction and the minimum

8 Two regimes

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

9 Gildener-Weinberg regime

Model studied in the Gildener-Weinberg regime in:

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]

Multi-Phase Critical Regime

In the multi-phase critical limit,
the two phases, *s* and *sh*, merge:

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

- Higgs massless at $\lambda_{HS}(\bar{\mu}) = 0$
- Another field to drive the running

Quantum Corrections

- In the critical limit, the dominant mass is

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

- 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

12 Quantum Corrections

Effective potential

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

Couplings run as

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

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

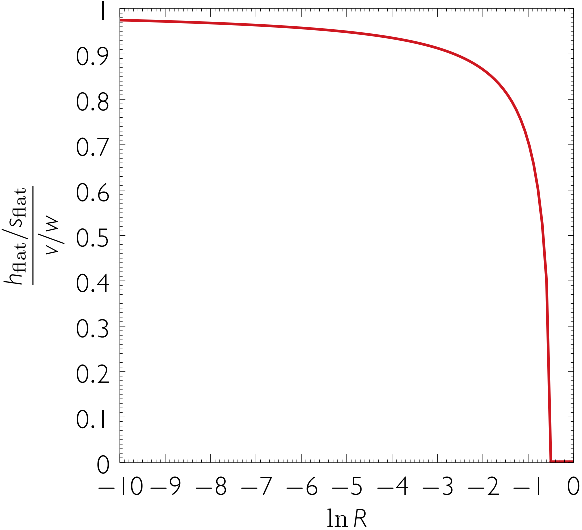
13 Quantum Corrections

- 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



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

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, $m_{s'}$, $\ln R$
- $\lambda_{S'}$ largely irrelevant (not too large)

16 Parameters

$$
\begin{aligned}
m_h^2 &\approx -\frac{\beta_{\lambda_{HS}}}{(4\pi)^2} w^2 \ln R \approx 2\lambda_H v^2, \\
m_s^2 &\approx 2\frac{\beta_{\lambda_S}}{(4\pi)^2} w^2, \\
m_{s'}^2 &\approx \frac{1}{2}\lambda_{SS'} w^2,
\end{aligned}
$$

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

17 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

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

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

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

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

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

19 Direct Detection

Effective coupling to nucleons

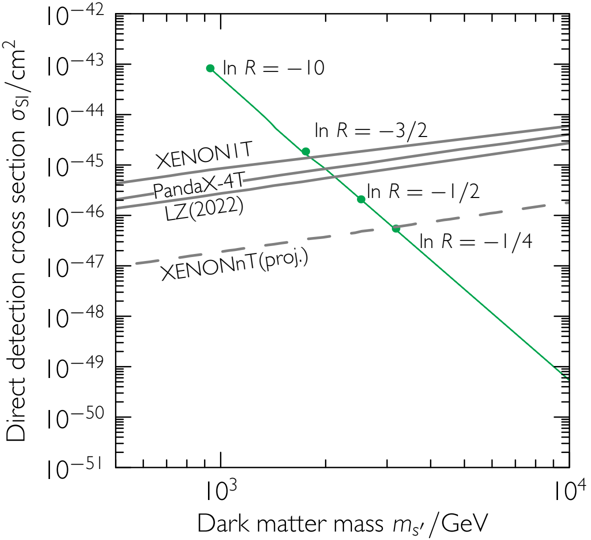
$$\frac{f_N m_N}{v} h\bar{N}N,$$

gives

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

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

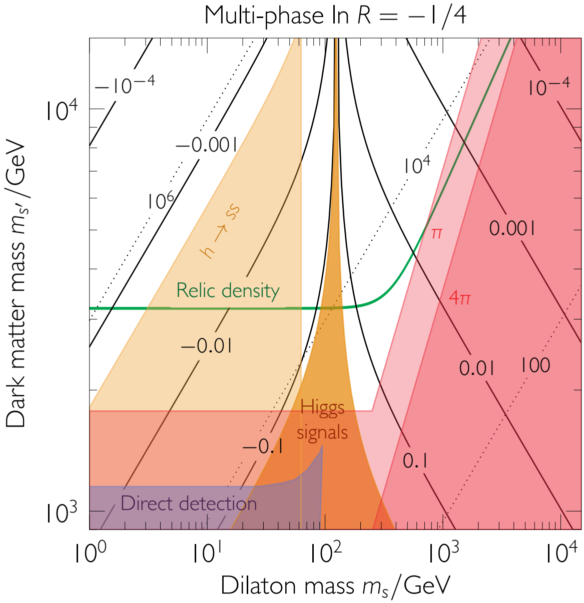
Direct Detection



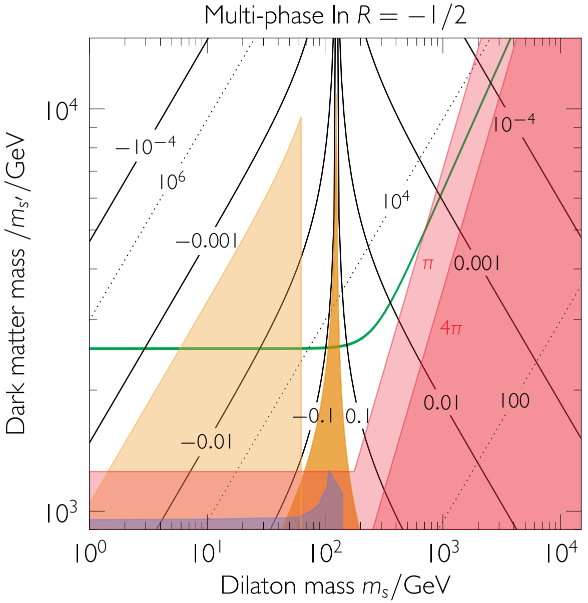
Parameter Space: Bounds

- Perturbativity: $\lambda_{HS}, \lambda_{SS'} < 4\pi$
- Fit of Higgs couplings
- $h \to ss$ decay
- Direct detection

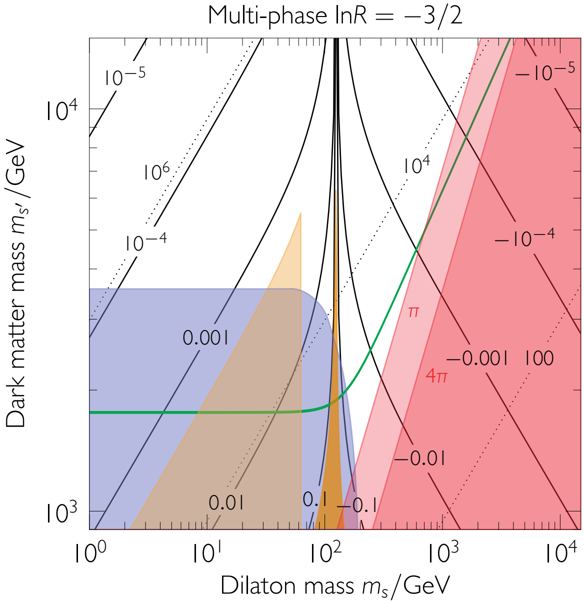
Parameter Space



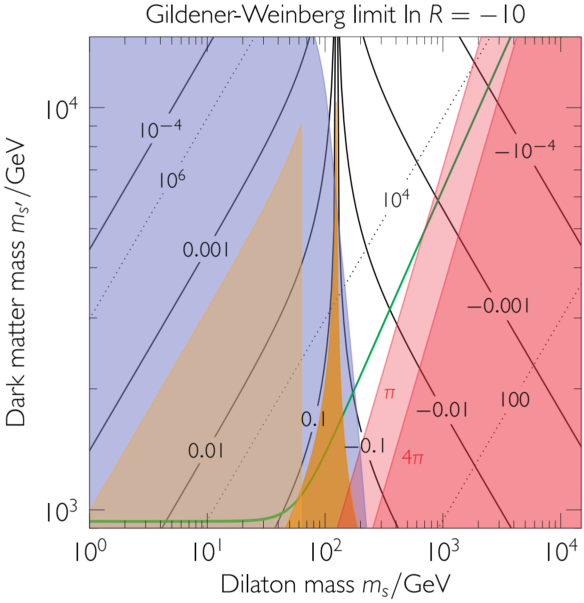
Parameter Space



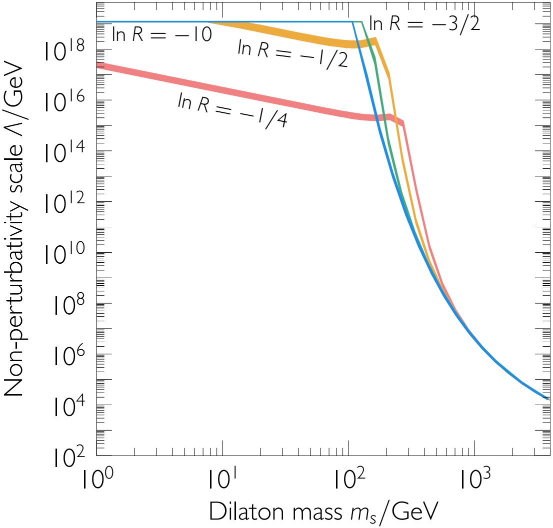
Parameter Space



Parameter Space



Perturbativity



In Progress: Freeze-in, and More

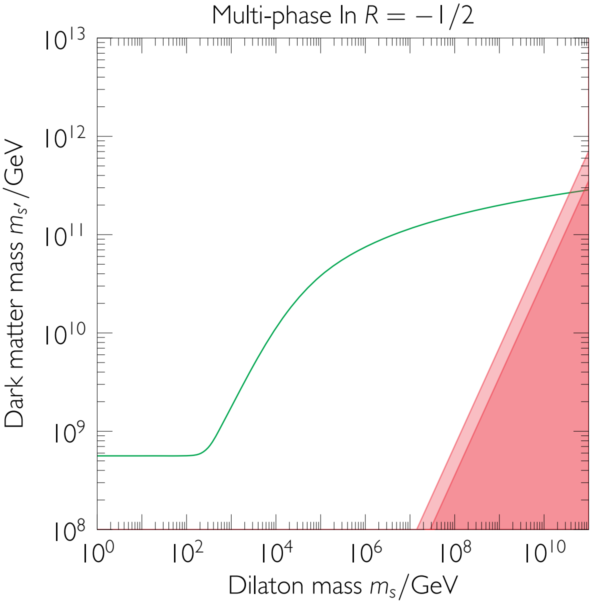
- Type-I seesaw mechanism with right-handed neutrinos N_R
- Yukawa Lagrangian

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

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

- Inflation with the dilaton s

28 In Progress: Freeze-in and More



Conclusions

- Classically scale-invariant model with 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
- In progress: freeze-in, leptogenesis & inflation in an extension of the model