Critical dark matter

Venno Vipp

In collaboration with: K. Kannike, N. Koivunen, A. Kubarski, L. Marzola, M. Raidal, and A. Strumia

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KBFI
University of Tartu

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Introduction

- We still don't know what dark matter is
- Need something to explain the small mass of the Higgs boson

We propose a model with two extra scalar fields and a scenario of multi-phase criticality

Coleman-Weinberg mechanism (1973)

- Proposed how a scale-invariant theory can dynamically acquire a mass scale and break symmetries, applying this to the Higgs field

$$V = \lambda_H |H|^4 \,, \quad \lambda_H \to \lambda_H(H)$$

- If the quartic $\lambda_H(H)$ becomes negative at low energies, then the scalar acquires a vacuum expectation value (VEV) $v \neq 0$ and mass $M_h \simeq \sqrt{\beta_{\lambda_H}} v \simeq$ of a few GeV
- In such a simple model the resulting mass is too small (Higgs mass is $\simeq 125$ GeV)

Gildener-Weinberg approach (1976)

- They added another scalar field S

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

- GW showed that dynamical symmetry breaking again happens when a combination of quartics $\lambda_H, \lambda_S, \lambda_{HS}$ cross 0 and become negative at low energies
- Different combinations (phases) give different results. The interesting case here is $\lambda_{HS} = -2\sqrt{\lambda_H \lambda_S} < 0$, $\lambda_H, \lambda_S > 0$ where both scalars get a VEV $w, v \neq 0$ and mass
- In such a case there is a direction $|H|/S = \sqrt{-\lambda_{HS}/\lambda_H}$ along which the potential $\lambda_H |H|^4$ is flat and only quantum corrections in this direction are important

Our model, multi-phase criticality

In addition to the condition of GW, $\lambda_{HS} = -2\sqrt{\lambda_H \lambda_S} < 0$, we also want $\lambda_S = 0$

- This scenario takes into account additional quantum corrections to λ_{HS} that push the true minimum of the potential away from the flat direction $|H|/S = \sqrt{-\lambda_{HS}/\lambda_H}$
- The coupling $\lambda_{HS} \simeq 0$ and its running becomes negligible so an additional field, S', is needed to drive the running

The first point affects electroweak symmetry breaking and Higgs mass generation. The second means that the coupling of the new field S' to H also affects symmetry breaking.

Our model, arXiv: 2204.01744

In our model, in order to get the right running couplings, we use the above approach and add an extra singlet S'

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

- We are interested in a case where the VEV for S' vanishes, and

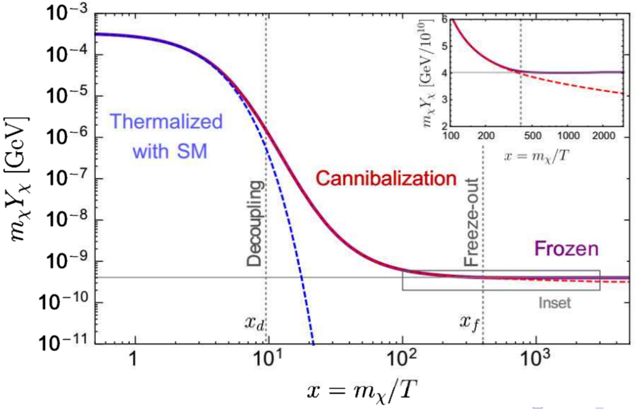
$$\lambda_S \ll \lambda_{HS} \ll \lambda_H, \lambda_{S'}, \lambda_{HS'}, \lambda_{SS'}$$

- Everything is expressed in terms of three parameters: dilaton mass m_S, dark matter mass $m_{S'}$, and R

$$\lambda_{HS'} \simeq -\frac{(4\pi)^2 m_H^2}{m_{S'}^2 \ln R} \,, \quad \lambda_{SS'} \simeq \frac{(4\pi)^2 m_S^2}{m_{S'}^2}$$

Freeze-out

A dark matter species χ, initially in thermal equilibrium with standard model particles, becomes decoupled when its rate of production becomes smaller than the rate of expansion $\Gamma \ll H(T)$. Afterwards DM self-annihilates until its number density becomes too small for new interactions to occur



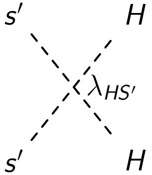
Relic abundance

$$\Omega_x = \frac{m_x n_x}{\rho_{\text{crit}}}$$

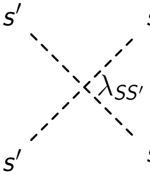
To match the observed relic abundance of DM ($\Omega_{DM} h^2 \simeq 0.12$) via freeze-out the annihilation cross section must be a certain value

$$\sigma_{\text{ann}} v \approx 4\pi^3 \frac{m_S^4 + 4 m_H^4 / \ln^2 R}{m_{S'}^6} \approx \frac{1}{(23\text{TeV})^2} \tag{1}$$

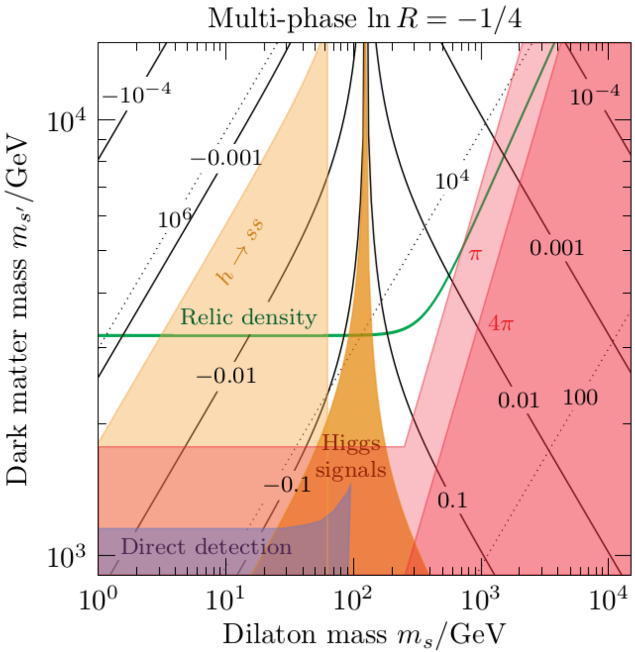
$\sigma_{\text{ann}} \propto$ |



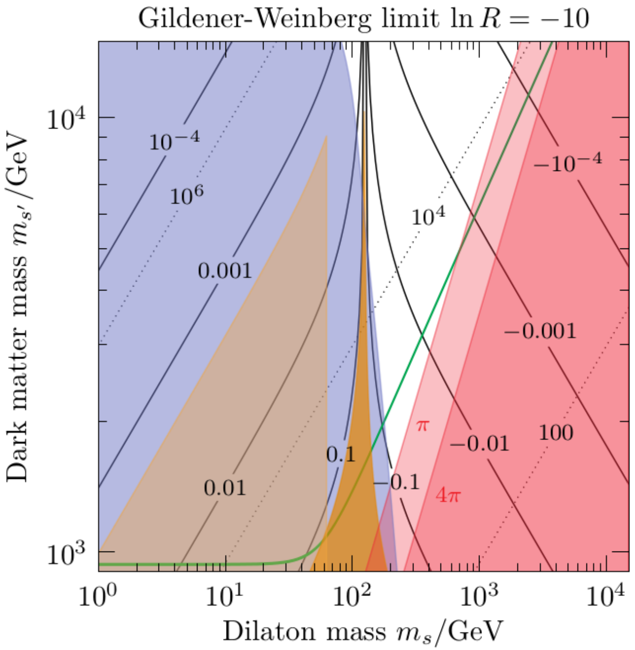
$|^2 +$ |



$|^2 \propto 4\lambda_{HS'}^2 + \lambda_{SS'}^2$



Multi-phase ln R = −1/4
Dark matter mass $m_{s'}$/GeV
Dilaton mass m_s/GeV
10^0
10^1
10^2
10^3
10^4
10^3
10^4
-10^{-4}
−0.001
−0.01
−0.1
10^{-4}
0.001
0.01
0.1
10^6
10^4
100
$h \to ss$
Relic density
Higgs signals
Direct detection
π
4π


Gildener-Weinberg limit $\ln R = -10$
10^{-4}
10^{6}
0.001
0.01
0.1
10^{4}
-0.1
-10^{-4}
-0.001
-0.01
100
π
4π
10^{4}
10^{3}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Dark matter mass $m_{s'}$/GeV
Dilaton mass m_s/GeV

Direct detection limits

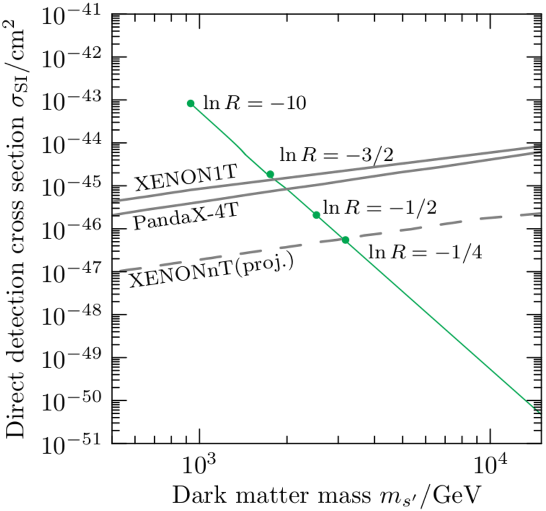
Normally, direct detection cs

$$\sigma_{\rm SI} \propto \frac{\lambda_{HS'}^2}{m_{S'}^2},$$

while in our case

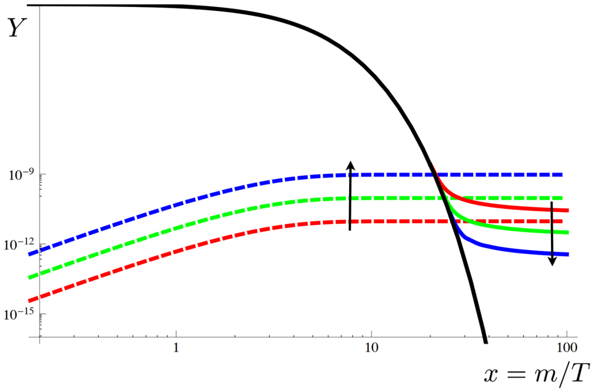
$$\sigma_{\rm SI} \approx \frac{64\pi^3 f_N^2 m_N^4}{m_{S'}^6}$$

The model is allowed for masses $m_{S'} \gtrsim 2$ TeV

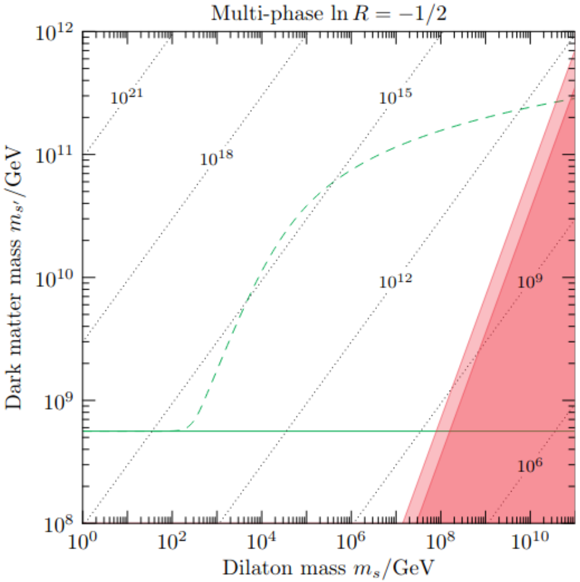


Ongoing work, freeze-in

Instead of 'freezing out', dark matter can 'freeze in'. In this case interactions with SM are highly suppressed and DM is not in equilibrium initially



Ongoing work, freeze-in



Conclusions

- We studied a model in which dynamical symmetry breaking is driven by the interactions with dark matter
- The scalar sector contains, besides the standard model Higgs boson, two gauge singlets: the dilaton and dark matter
- We find a tight connection between dark matter and Higgs boson phenomenology
- The model is testable at future experiments