Inflation as a probe to Dark Matter properties

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The Model and low energy particle phenomenology

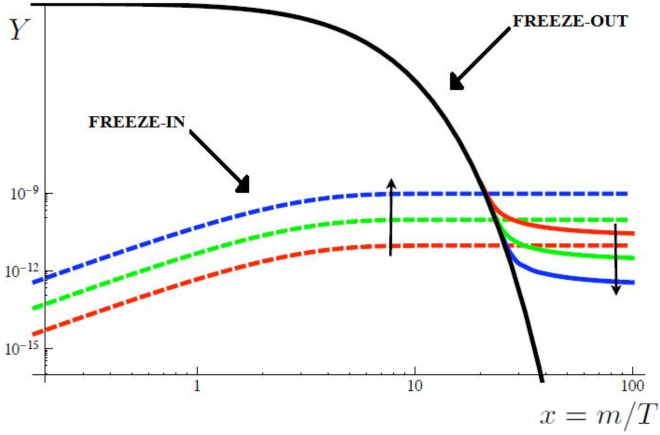
- The scalar sector of the model is specified by the potential

$$V(\Phi, s) = m_{\rm h}^2\Phi^\dagger\Phi + \lambda_{\rm h}(\Phi^\dagger\Phi)^2 + \frac{1}{2}m_{\rm s}^2 s^2 + \frac{\lambda_{\rm s}}{4}s^4 + \frac{\lambda_{\rm sh}}{2}\Phi^\dagger\Phi s^2$$

- Here Φ and s are, respectively, the usual Standard Model Higgs doublet and a real singlet scalar.
- The coupling between Φ and s acts as a portal between the Standard Model and an unknown Dark Sector (the so-called Higgs portal).

Dark Matter production mechanisms

- There are basically two mechanisms for dark matter production: freeze-out and freeze-in[1]



[1] The original picture is from Hall et al. (arXiv:0911.1120)

The Freeze-In

- If the portal coupling takes a value $\lambda_{\rm sh} \lesssim 10^{-7}$, the singlet s never thermalizes with the SM $\Rightarrow$ only freeze-in is possible (this is sometimes called a FIMP scenario).
- In the standard case, only low-temperature ($T \lesssim T_{\rm EW}$) processes such as $h \to ss$ have been considered.
- It is also possible to slowly produce a sizeable fraction of the observed dark matter abundance via particle production from a time-dependent background field already at temperatures above the EW scale.

Cosmic Inflation

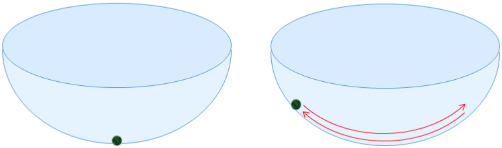
- An era of rapid expansion, $a \propto e^{Ht}$, in the very early universe.
- We assume the scalar fields are spectator fields during inflation.
- The scalar fields will typically acquire fluctuations proportional to the inflationary scale, $h, s \simeq H_* \lesssim 10^{14}$ GeV[2].
- During inflation, the field amplitudes perform a random walk at superhorizon scales[3].

[2] BICEP2 & Planck collaborations (arXiv:1502.00612)

[3] Starobinsky & Yokoyama (arXiv:astro-ph/9407016)

Initial conditions set by Inflation

- We do not know the field values within any patch, we just know that typically $\sqrt{\langle h^2 \rangle}, \sqrt{\langle s^2 \rangle} \simeq H_* \lesssim 10^{14}$ GeV.
- We take these results as inflationary predictions for the initial values of the scalar fields.
- After inflation[4], the field values start to oscillate about the minima of their potential.



A marble in a bowl.

[4] We assume an instant reheating of the universe.

Particle production from a time-dependent potential: an example

- The background produces two singlet particles, $s_0 \to ss$, with an amplitude[5]

$$|\mathcal{M}|_{s_0 \to ss} \sim \int_{-\infty}^{\infty} dt \langle ss|\hat{V}(t)|0\rangle,$$

where $\hat{V}(t)$ is the interaction part of the Hamiltonian,

$$\hat{V}(t) = -\lambda_{\rm s} s_0^2(t) \int d^3x \hat{s}\hat{s}.$$

- The corresponding energy dissipation rate is

$$\Gamma_{s_0 \to ss} \simeq 4 \times 10^{-4} \lambda_{\rm s}^{3/2} s_0(t)$$

[5] See e.g. Abbott et al. (Phys.Lett. B117 (1982) 29), Ichikawa et al. (arXiv:0807.3988).

Boltzmann equation governs the evolution of DM number density

- Time-evolution of the scalar background number density $n_{s_0} \equiv \rho_{s_0}/m_{s,\mathrm{eff}}$ is given by

$$\dot{n}_{s_0} + 3Hn_{s_0} \simeq -\Gamma_{s_0 \to ss} n_{s_0},$$

and the singlet particle number density by

$$\dot{n}_{s} + 3Hn_{s} \simeq +\Gamma_{s_0 \to ss} n_{s_0}.$$

- By knowing the Γ, these equations can be solved analytically.

The background decay

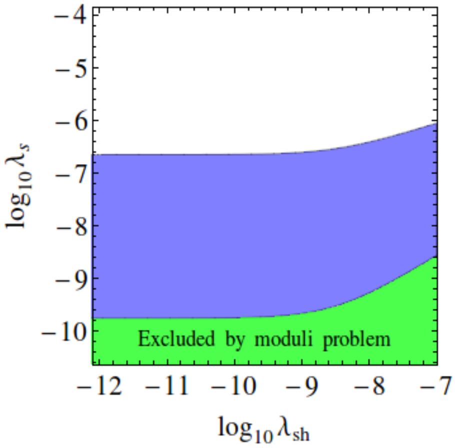
- Solution for the background number density is

$$n_{s_0} \simeq n_{s_0}(t_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3 \exp\left(-\frac{\Gamma_{s_0\to ss}(t)}{H}\right) \ .$$

- We see the background decays as $\Gamma(t) \simeq H$, and the comoving number density of singlet particles freezes to a constant value:

$$a^3 n_s \simeq \left(n_{s_0} a^3\right)_{t=t_*} \ ,$$

The total Dark Matter yield



- In this figure $H_* \simeq 10^{10}$ GeV and $m_s = 20$ MeV.

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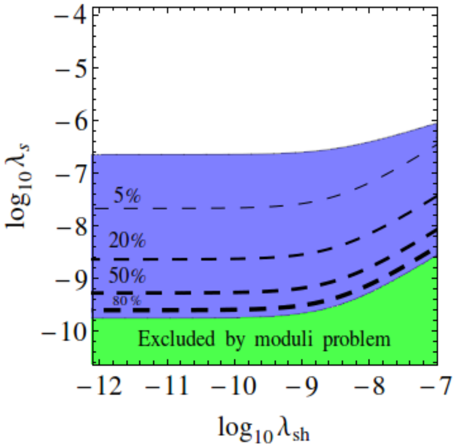

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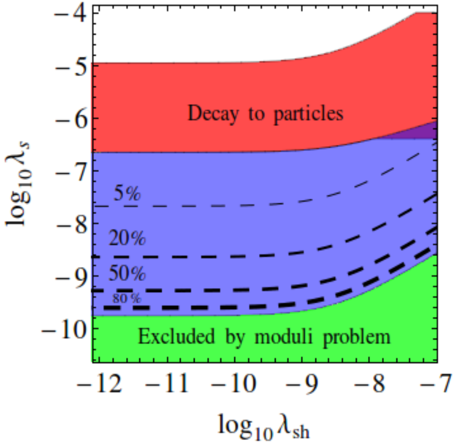

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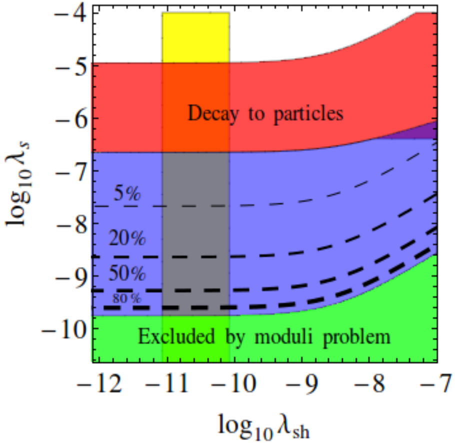

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The Isocurvature Problem

- The observational bounds are significantly different depending on whether the singlet constitutes isocurvature or adiabatic dark matter.
- While the dark matter component sourced by the primordial scalar field clearly is isocurvature and therefore strictly constrained, the situation is less clear when the production of singlet particles through Higgs decay is important.
- Any additional couplings between the SM and the portal sector would also affect the situation.

Outlook: Extensions of the Model

- What if the dark sector contained more fields?
- Consider the interaction $gs\bar{\psi}\psi$ between singlet scalar and singlet fermion. This gives an extra decay channel[6]

$$n_{s_0} \simeq n_{s_0}(t_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3 \exp\left(-\frac{\Gamma_{s_0\to ss}(t)}{H} - \frac{\Gamma_{s_0\to\bar{\psi}\psi}(t)}{H}\right) .$$

- Leads to interesting dynamics as, for example, the fermionic DM component can be produced from the primordial background, and the scalar component from the SM sector.

[6] K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen: *Work in progress*.

Conclusions

- Formation and presence of a scalar background is a typical consequence in a theory containing scalar fields.
- The inflationary dynamics can affect physics also below the EW scale, and model computations need to be revisited.
- We have found a novel connection between dark matter abundance and inflationary scale.
- Cosmic inflation can be used to constrain the high-energy regime of extensions of the Standard Model.