Inflationary Imprints on Dark Matter

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The Model and low energy particle phenomenology

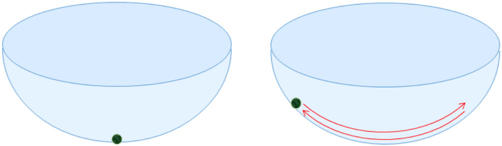
- The scalar sector of the model is specified by the potential

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

- 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).

Initial conditions set by Inflation

- If the scalar fields are light during cosmic inflation, they will typically acquire fluctuations proportional to the inflationary scale[1], $h, s \simeq H_* \lesssim 10^{14}$ GeV.
- We take these results as inflationary predictions for the initial values of the scalar fields.
- After inflation, the fields start to oscillate about the minima of their potential.

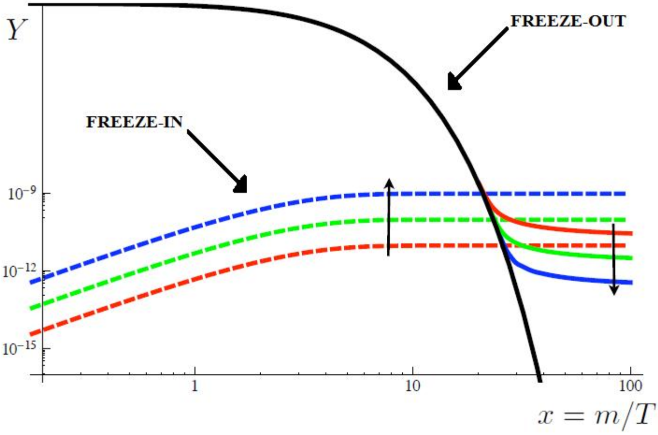


A marble in a bowl.

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

Dark Matter production mechanisms

- There are basically two mechanisms for dark matter production: freeze-out and freeze-in[2]



[2] 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 and dark matter is born cold.
- 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.

Particle production from a time-dependent potential: an example

- The background produces two singlet particles, $s_0 \to ss$, with an amplitude[3]

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

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

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

[3] 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 $n_{s_0} \equiv \rho_{s_0}/m_{s,\text{eff}}$ is given by

$$\dot{n}_{s_0} + 3Hn_{s_0} = -\Gamma_{h\to sh}n_h - \Gamma_{s_0\to ss}n_{s_0},$$

and the singlet particle number density by

$$\dot{n}_s + 3Hn_s = +\Gamma_{h\to sh}n_h + \Gamma_{s_0\to ss}n_{s_0}.$$

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

The background decay

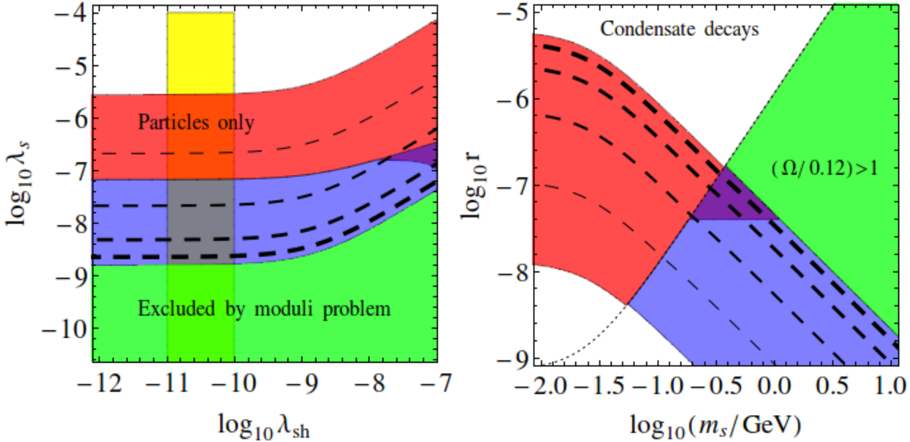
- Solution for the background number density is

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

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

$$a^3 n_s \simeq \left(\frac{\Gamma_{h\to sh}}{\Gamma_{s_0\to ss}} n_{\rm h} a^3 + n_{s_0} a^3\right)_{t=t_{\rm osc}} ,$$

The total Dark Matter yield



- Left panel: $r = 10^{-8}$ (corresponding to $H_* \simeq 10^{10}$ GeV) and $m_s = 10$ MeV. Right panel: $\lambda_s = 10^{-6}$, $\lambda_{sh} = 10^{-8}$.

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, 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.

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.
- The result constrains also those models in which the frozen-in scalar acts only as a mediator and decays further to the actual Dark Matter particle.

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[4]

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

- 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.

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