Inflationary constraints on Dark Matter properties

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What do we study?

- Our focus is on testing the Standard Model extensions through a broad range of their cosmological imprints.
- The key new ingredient: the consistent inclusion of inflationary initial conditions for the typical scalar sector encountered in extensions of SM.
- In particular, we study initial conditions for dark matter production and for phase transitions (baryogenesis).

Prelude: What have we found?

- Physics below the electroweak scale may carry memory of non-vacuum initial conditions generated by inflation.
- We have identified the parameter space where initial conditions will significantly affect baryogenesis at the electroweak phase transition[1].
- A novel interplay between inflationary dynamics and dark matter properties places stringent constraints on viable mass scales and coupling values in SM extensions[2,3] $\Rightarrow$ This talk!

[1] K. Enqvist, S. Nurmi, TT, K. Tuominen (arXiv: 1407.0659)

[2] S. Nurmi, TT, K. Tuominen (arXiv: 1506.04048)

[3] K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen (*Work in progress*)

The Model

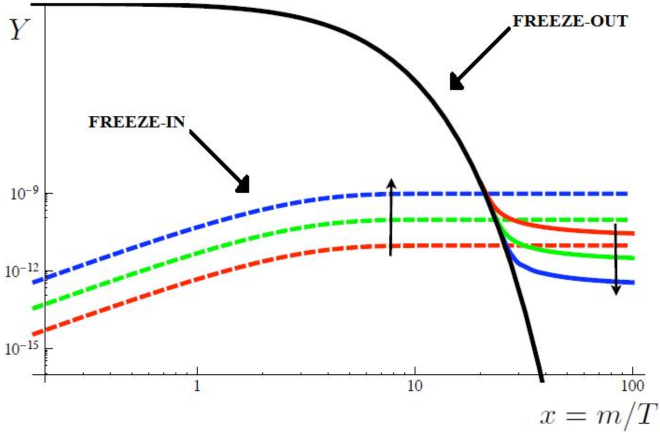
- The scalar sector of the model is specified by the potential

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

- 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).
- The model may explain the observed DM abundance or the origin of baryon asymmetry.

Dark Matter production mechanisms

- There are basically two mechanisms for dark matter production: freeze-out and freeze-in[4]



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

The Freeze-Out

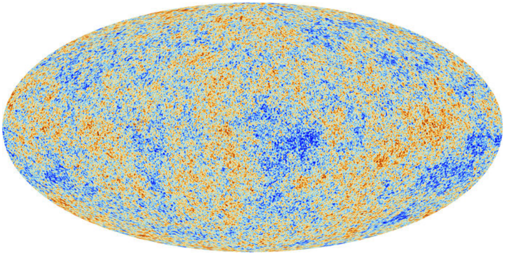
- Dark matter is initially in thermal equilibrium with the SM particles. This requires a rather strong coupling, $\lambda_{\rm sh} \simeq 0.1$.
- May lead to a WIMP miracle: thermal relic with weak cross-section and a mass $m_{\rm s} \sim$ EW scale gives the right relic abundance.
- May also lead to a strong electroweak phase transition required by any successful baryogenesis scenario.

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

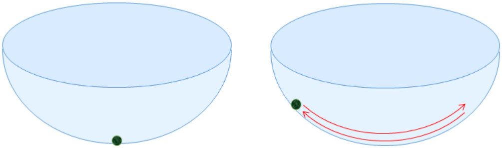
- An era of rapid expansion, $a \propto e^{H(t)t}$, in the very early universe.
- Driven by new physics(?) – inflaton?
- Inflaton fluctuates during inflation – explains the origin of large-scale structure of the universe.
- Inflation explains also homogeneity and flatness of the universe.



CMB as seen by Planck satellite.

Spectator field dynamics during Inflation

- We assume the scalar fields h, s 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[5].
- During inflation, the field amplitudes perform a random walk at superhorizon scales[6].



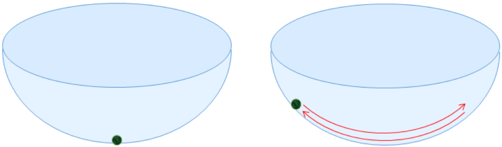
A (quantum) marble in a bowl.

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

[6] 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 $h_*, s_* \simeq H_* \lesssim 10^{14}$ GeV in a patch of the size of our observable universe.
- We take these results as inflationary predictions for the initial values of the scalar fields.
- When do the fields relax down to their minima? What happens to the energy stored in the fields?



A (quantum) marble in a bowl.

Field dynamics after Inflation

- Time evolution of a homogeneous scalar field s is given by

$$\ddot{s} + 3H(t)\dot{s} + \frac{dV}{ds} = 0,$$

where

$$V = \frac{\lambda_s}{4}s^4 + \frac{1}{2}m_s^2 s^2$$

is the background potential (quartic/quadratic).

- Solution: $s(t) = s_0(t) \times cos(\omega t)$, where $s_0(t) \propto H_*$.

- Expand the Lagrangian around $s_0(t)$: leads to interaction terms[7] such as $\lambda_s s_0(t)^2 s^2$.

[7] Such interactions are usually encountered in reheating models.

Particle production from a time-dependent potential: an example

- The background produces two singlet particles, $s_0 \to ss$, with an amplitude[8]

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

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

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

[8] 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 $n_{s_0} \equiv \rho_{s_0}/m_{s,\rm eff}$ 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

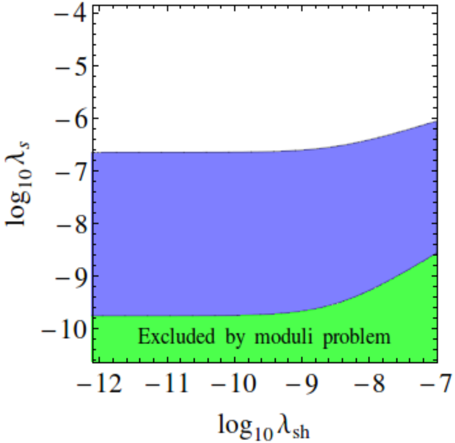
$$n_{s_0} \simeq n_{s_0}(t_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3 \exp\left(-\frac{\Gamma_{s_0\to ss}(t)}{H}\right) \ .$$

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

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

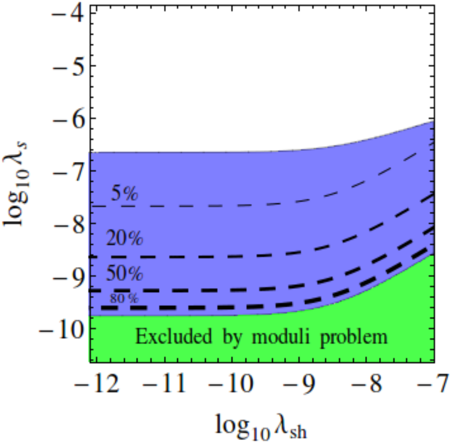
- Freeze-in at $T \gg T_{\rm EW}$!

Dark Matter from Primordial Field



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

Dark Matter from Primordial Field



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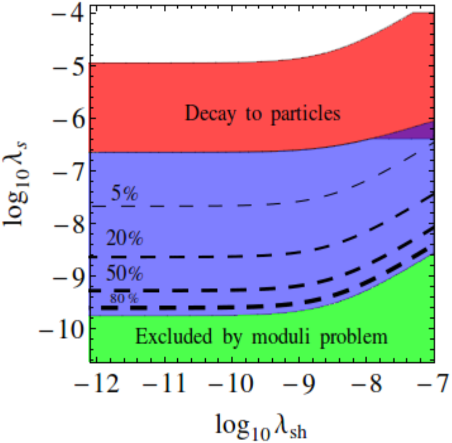

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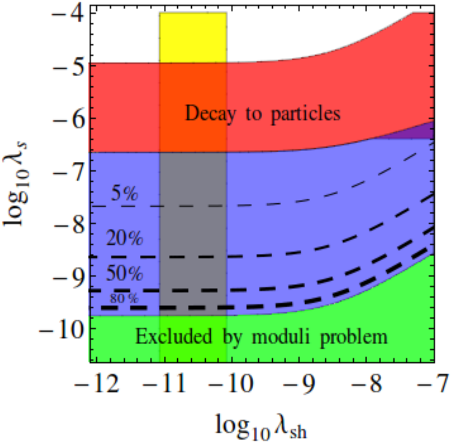


- In this figure $H_* \simeq 10^{10}$ GeV and $m_s = 20$ MeV.

The Isocurvature Problem

- The observational bounds are significantly different depending on whether the singlet constitutes isocurvature[9] 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.

[9] Isocurvature perturbations are also called *entropy* perturbations.

Extensions of the simplest model

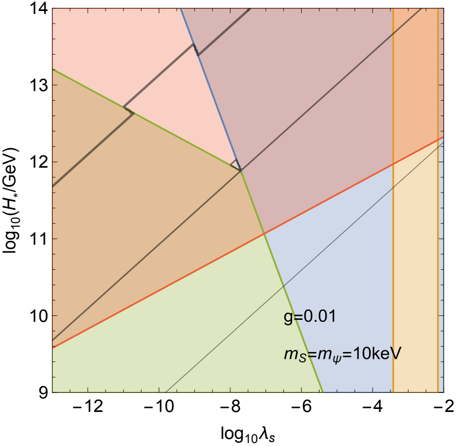
- What if the dark sector contained more fields?
- Consider the interaction $gs\bar{\psi}\psi$ between singlet scalar and singlet fermion. This gives an extra decay channel[10]

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

- The primordial scalar field s_0 can now decay into fermions instead of decaying into quanta of its own field.

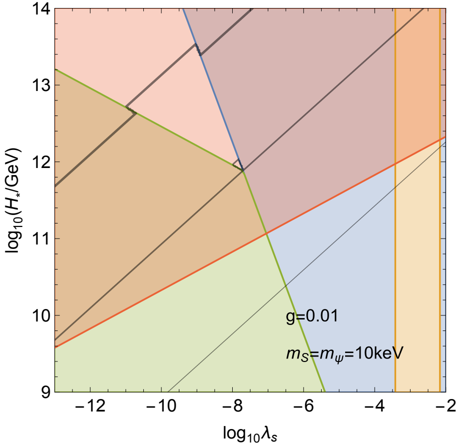
[10] K. Kainulainen, S. Nurmi, TT, K. Tuominen, V. Vaskonen (*Work in progress*)

Preliminary results



- Red: Excluded by isocurvature, Yellow (Green): Decay to fermions in quartic (quadratic) potential, Blue: Decay to scalars.

Preliminary results



- Contours from thickest to thinnest: 1, 10^{-6}, 10^{-9} of the observed DM abundance.

Preliminary results II

- It seems that a great majority of the observed DM abundance has to be produced by other mechanisms.
- The formation of primordial scalar fields however puts stringent constraints on model parameters.
- New physics even with tiny couplings to the SM can be constrained by carefully investigating their dynamics both during and after inflation.

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.

Take-home message

Cosmic inflation can be used to constrain the high-energy regime of extensions of the Standard Model.

Backup slides

What about the Higgs field?

- Also Higgs has an initial field value $h_* \sim H_*$.
- Assuming an instant reheating at T_*, Higgs's interaction with thermal bath gives it a huge thermal mass $m_{\rm h} \sim T$.
- Decay of the primordial Higgs field is delayed by thermal blocking but interactions with gauge bosons thermalize the Higgs field at $T \sim 10^{-2} T_*$.
- Physics below this temperature are insensitive for the non-vacuum initial conditions of the Higgs field[11].

[11] K. Enqvist, S. Nurmi, TT, K. Tuominen (arXiv: 1407.0659)

Initial conditions for phase transitions

- If the portal coupling allows *s* to thermalize, $\lambda_{\rm sh} \gtrsim 10^{-7}$, the singlet sector will typically relax to its vacuum stage by the EW scale.

- In that case, SM+singlet scalar baryogenesis mechanism[12]is not hampered by the non-vacuum initial conditions generated by inflation.

- What about other phase transitions at $T \gg T_{\rm EW}$? $\Rightarrow$ Remain to be studied!

[12] J. Cline & K. Kainulainen (arXiv: 1210.4196)