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The many faces of the inflaton field

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Open problems in cosmology

Evidence for Dark Matter

- Great deal of evidence for the existence of dark matter: rotational velocity curves of galaxies, Bullet Cluster[1], acoustic peaks in the Cosmic Microwave Background (CMB) radiation spectrum...
- Still the nature of dark matter is unknown

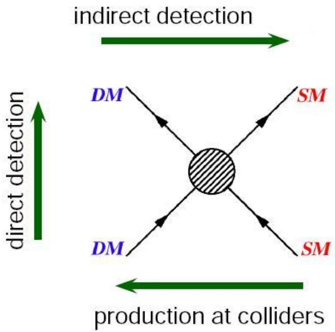
[1] Image: Chandra X-ray Observatory

What is Dark Matter?

- What is the correct explanation for the invisible matter content observed in the universe? Does the dark matter particle exist? Or are there many dark matter particles?
- Are they WIMP's, FIMP's, SIMP's, GIMP's, PIDM's, WISP's, ALP's, Wimpzillas, or sterile neutrinos? Or should gravity be modified?
- How can we tell which model is the correct one (if any)?

Search for Dark Matter

- Many on-going experiments exist[2]



- Yet no conclusive detection.

[2] Original image: Max-Planck-Institut Für Kernphysik

Matter–antimatter asymmetry

- Why is there more matter than antimatter? How and at what point in the history of the universe was this asymmetry generated?
- Electroweak baryogenesis remains as a viable candidate for explaining the origin of this asymmetry.
- It requires deviation from thermal equilibrium, i.e. a strongly first order phase transition at the EW scale ($T \sim 100\mathrm{GeV} \sim 10^7\mathrm{K}, t \sim 10^{-11}\mathrm{s}$)

Cosmic inflation

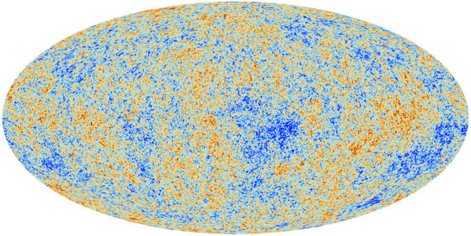


Image: Planck/ESA

- Must explain the observed curvature perturbations (+ several fine-tuning problems) $\Rightarrow$ Cosmic inflation
- Inflaton: SM Higgs? $f(R)$? Flat direction in MSSM? Axion? ...

A simple question

- What else can the inflaton field be responsible of?
- Dark Matter production? Could it even be dark matter?
- Matter-antimatter asymmetry? If the asymmetry is produced by electroweak baryogenesis, a crucial requirement is a strong first order phase transition, which is not possible in the SM only. Could the inflaton provide that?
- What is the minimal model that explains all these open problems?

The Higgs Portal Model

The Higgs Portal Model

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

$$V(s,\phi) = \mu_\phi^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2 + \mu_1^3 s + \frac{\mu_s^2}{2} s^2 + \frac{\mu_3}{3} s^3 + \frac{\lambda_s}{4} s^4$$
$$+ \mu_{hs} (\phi^\dagger \phi) s + \frac{\lambda_{hs}}{2} (\phi^\dagger \phi) s^2 + V_{gravity},$$

- Here Φ and s are, respectively, the usual Standard Model Higgs doublet and a real singlet scalar.

- The couplings μ_{hs} and λ_{hs} act as portals between the Standard Model and an unknown Hidden Sector (the so-called Higgs portal).

- We choose $V_{gravity} = \frac{1}{2}(\xi_h \Phi^\dagger \Phi + \xi_s s^2) R$.

Dynamics

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

$$V(s,\phi) = \mu_\phi^2\phi^\dagger\phi + \lambda_{\rm h}(\phi^\dagger\phi)^2 + \mu_1^3 s + \frac{\mu_{\rm s}^2}{2}s^2 + \frac{\mu_3}{3}s^3 + \frac{\lambda_{\rm s}}{4}s^4 + \mu_{\rm hs}(\phi^\dagger\phi)s + \frac{\lambda_{\rm hs}}{2}(\phi^\dagger\phi)s^2 + \frac{1}{2}(\xi_{\rm h}\Phi^\dagger\Phi + \xi_{\rm s}s^2)R,$$

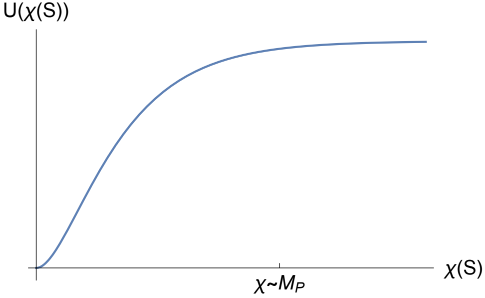
- Depending on the chosen symmetries and coupling values, different dynamics may arise.

- For example, DM stability requires $\mu_1 = \mu_3 = \mu_{\rm hs} = 0$, EWPT (typically) requires large $\lambda_{\rm hs}$ and $\lambda_{\rm s}$, and inflation requires $\lambda_{\rm s}/\xi_{\rm s}^2 \simeq 10^{-10}$.

Cosmic inflation

Starobinsky-like inflation

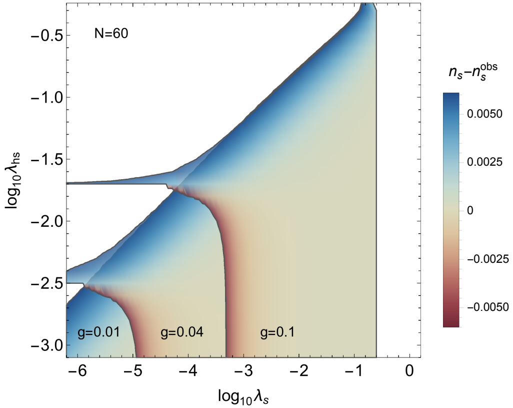
- At large fields values the Einstein frame potential is $U(\chi_s) \simeq \lambda_s M_P^4/\xi_s^2 \Rightarrow$ plateau inflation
- The observed amplitude of the curvature power spectrum requires $\lambda_s/\xi_s^2 \sim 10^{-10}$.



The classical *s* potential (in the Einstein frame)

Inflationary observables

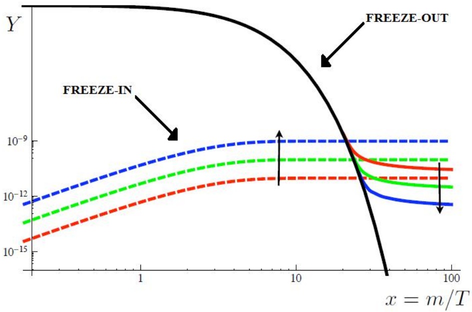
- At classical level, we find $n_s \simeq 0.968$, $r = \mathcal{O}(10^{-3})$; compare to Planck results: $n_s = 0.9677 \pm 0.0060$, $r < 0.11$.
- Quantum corrections affect predictions for inflationary observables $\mathcal{P}_\zeta$, n_s, and r.



Dark matter production

S-inflation

- Let us study the *S*-inflation model[3]: the new scalar *s* is both the inflaton and the dark matter particle
- Depending on the strength of $\lambda_{\rm hs}$, the dark matter abundance can be produced either by freeze-out or freeze-in mechanism[4]



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[3] R. Lerner and J. McDonald (arXiv:0909.0520)

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

The fimplaton model

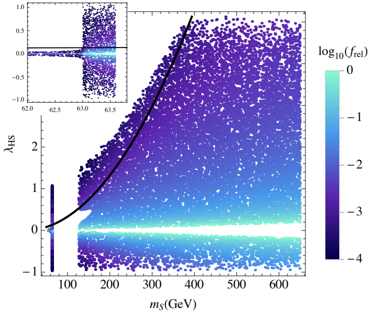
- We study a scenario where s is both a FIMP and the inflaton (a 'fimplaton')[5]. DM abundance is produced by decays of Higgs bosons at $T \sim m_{\rm h}$.
- We find the scenario works for $10^{-9} < \lambda_{\rm s} < \lambda_{\rm hs} < 10^{-7}$, $1\,{\rm keV} \lesssim m_{\rm s} \lesssim 100$ MeV, $\xi_{\rm s} = \mathcal{O}(1)$
- The predictions for n_s and r make the scenario distinguishable from other models of the same type (Higgs inflation, Starobinsky inflation, original S-inflation)

[5] T. Tenkanen (arXiv:1607.01379); the original WIMP + inflaton has been studied extensively in the literature

Electroweak phase transition

S-inflation + EWPT

- Let us then ask can one realize both inflation and a strong electroweak phase transition in the S-inflation model[6]
- We already know both a strong EWPT and generation of the observed DM abundance cannot be simultaneously realized in the singlet scalar model[7]



[6] T. Tenkanen et al. (arXiv:1606.06063).

[7] The figure is from Alanne et al. (arXiv:1407.0688).

A Strong EWPT

- In this model a strong electroweak phase transition can be realized already at tree-level[8].

- This requires the transition happens from a minimum in s-direction (at non-zero temperature) to the electroweak broken minimum at $(h, s) = (v, 0)$.

- Requiring the model to
  - describe inflation successfully
  - be compatible with the LHC and LUX data, and
  - yield a strong first order electroweak phase transition

  we identify the regions of the parameter space where the model is viable.

[8] See J. Cline and K. Kainulainen (arXiv:1210.4196) for details.

Additional degrees of freedom

- To probe the sensitivity of the constraints on additional degrees of freedom, we also introduce a fermion (sterile neutrino) ψ with

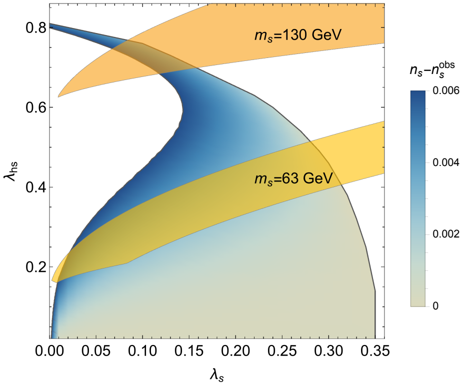
$$\mathcal{L}_{\rm Hidden} = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi + igs\bar{\psi}\psi$$

- Additional dof's will eventually be necessary when extending the model to account for sufficient CP violation relevant for applications towards electroweak baryogenesis

- Both s and ψ can also be dark matter candidates

A Strong EWPT: Z_2–symmetric potential (no ψ)

- Dynamics can be studied analytically. If s is stable, it's properties are strongly constrained by DM overclosure and LHC constraints[9].

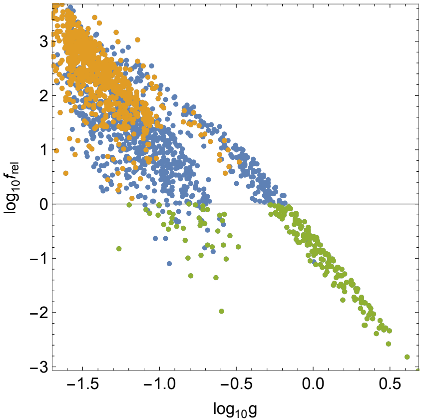


- The yellow and orange bands show where a Z_2–symmetric s gives a strong EWPT. Here $g = 0$.

[9] See J. Cline et al. (arXiv:1306.4710) for details.

A Strong EWPT: General potential (with ψ)

- Dynamics has to be studied numerically. We perform a Monte Carlo scan over the parameter space.



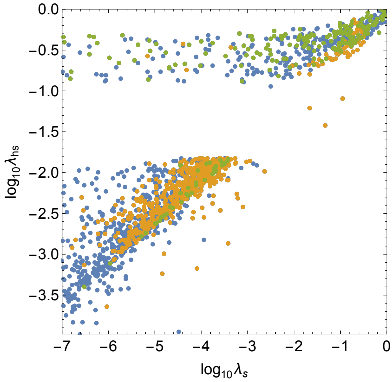
- All points give a strong EWPT and are compatible with the LHC data. Orange points give successful inflation and green points are in agreement with the LUX constraints.

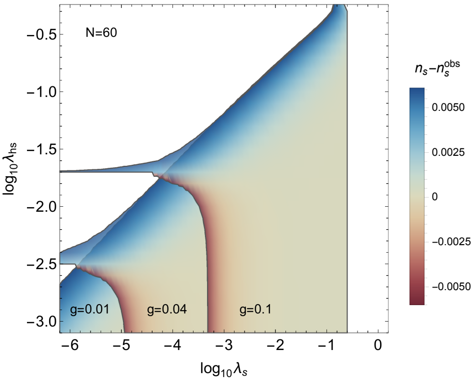
Active–sterile neutrino mixing

- There is a severe tension between obtaining a small enough dark matter relic density and compatibility with the inflationary constraints.
- However, this difficulty is easily avoided: we allow for mixing between the active and sterile neutrinos
- To alleviate the overclosure constraint we require ψ to decay before the big bang nucleosynthesis at $T \simeq 1$ MeV through the mixing.

The Results

- All points give a strong EWPT and are compatible with the LHC data. With $\sin^2\theta \gtrsim 10^{-11}$, orange points give successful inflation **and** are in agreement with the LUX constraints.





Inflation and the EW scale

- In more complicated model setups, the inflationary dynamics can be even more entwined to the physics at the EW scale.
- The inflaton may be responsible for the existence of the EW scale $\Rightarrow$ addresses the so-called hierarchy problem.
- See more: 'Inflation and pseudo-Goldstone Higgs' by T. Alanne, F. Sannino, TT, K. Tuominen (arXiv:1611.04932)

Conclusions

Conclusions (Inflation + DM)

- We showed both inflation and generation of the dark matter abundance can be successfully realized within a model consisting of SM $+s+\xi s^2 R$
- This is possible even if s interacts only feebly with the SM particles (s is a 'fimplaton')
- The fimplaton model can be distinguished from other models of the same type by measuring n_s and r more accurately

Conclusions (Inflation + EWPT)

- We showed both inflation and a strong first order electroweak phase transition can be successfully realized within a model consisting of SM $+s+\psi+\xi s^2 R$.
- Our analysis can be easily generalized to cover also other models with or without a non-minimal coupling to gravity.
- At the advent of advanced gravitational wave detector era it would be interesting to further study what information could be extracted also from inflationary models by studying also other phase transitions in detail.

Epilogue: what if new physics cannot be tested at colliders?

- 'Reheating the Standard Model from a hidden sector' (TT, Vaskonen, arXiv:1606.00192)
- 'Observational Constraints on Decoupled Hidden Sectors' (Heikinheimo, TT, Tuominen, Vaskonen, arXiv:1604.02401)
- 'Isocurvature Constraints on Portal Couplings' (Kainulainen, Nurmi, TT, Tuominen, Vaskonen, arXiv:1601.07733)
- 'Inflationary Imprints on Dark Matter' (Nurmi, TT, Tuominen, arXiv:1506.04048)