A Strong Electroweak Phase Transition From The Inflaton Field

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Cosmic inflation

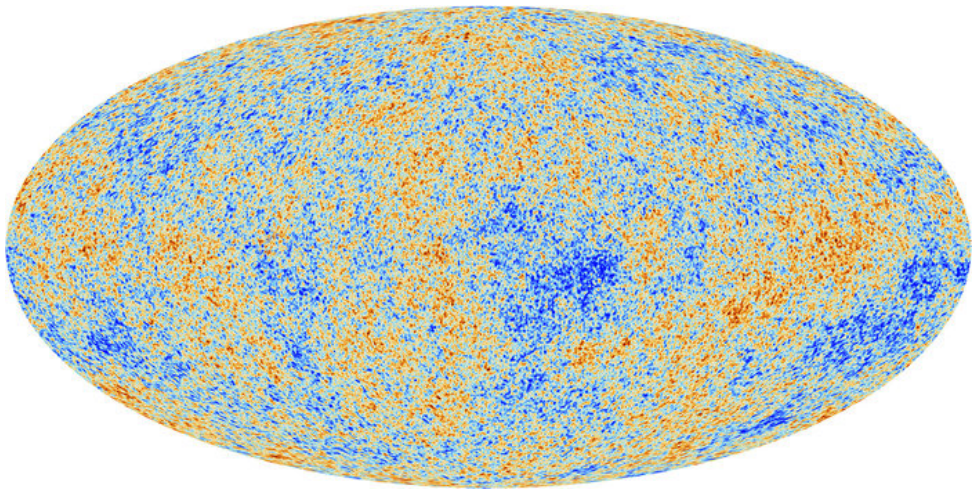


Image: Planck/ESA

- 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? $\Rightarrow$ *S*-inflation (wimplaton/fimplaton), asymmetric or incomplete reheating etc. – Studied a lot!
- Matter-antimatter asymmetry? $\Rightarrow$ Maybe? Baryogenesis during reheating studied to some extent.
- If matter-antimatter asymmetry is produced by electroweak baryogenesis, a crucial requirement is a strong first order phase transition, which is not possible in the SM[1].

  $\Rightarrow$ Could the inflaton provide that?

[1] See TT et al. (arXiv:1611.04932) for how the inflaton may be responsible for the existence of the EW scale.

The Higgs Portal Model

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

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

- 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 $V_\mathrm{gravity} = \frac{1}{2}(\xi_\mathrm{h}\Phi^\dagger\Phi + \xi_\mathrm{s}s^2)R$ and take s to drive inflation.

Additional dof's

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

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

- We also allow active–sterile neutrino mixing with $\sin^2\theta \lesssim 0.007$ (constraint from the invisible decay width of the Z boson).

- Both s and ψ are also Dark Matter candidates.

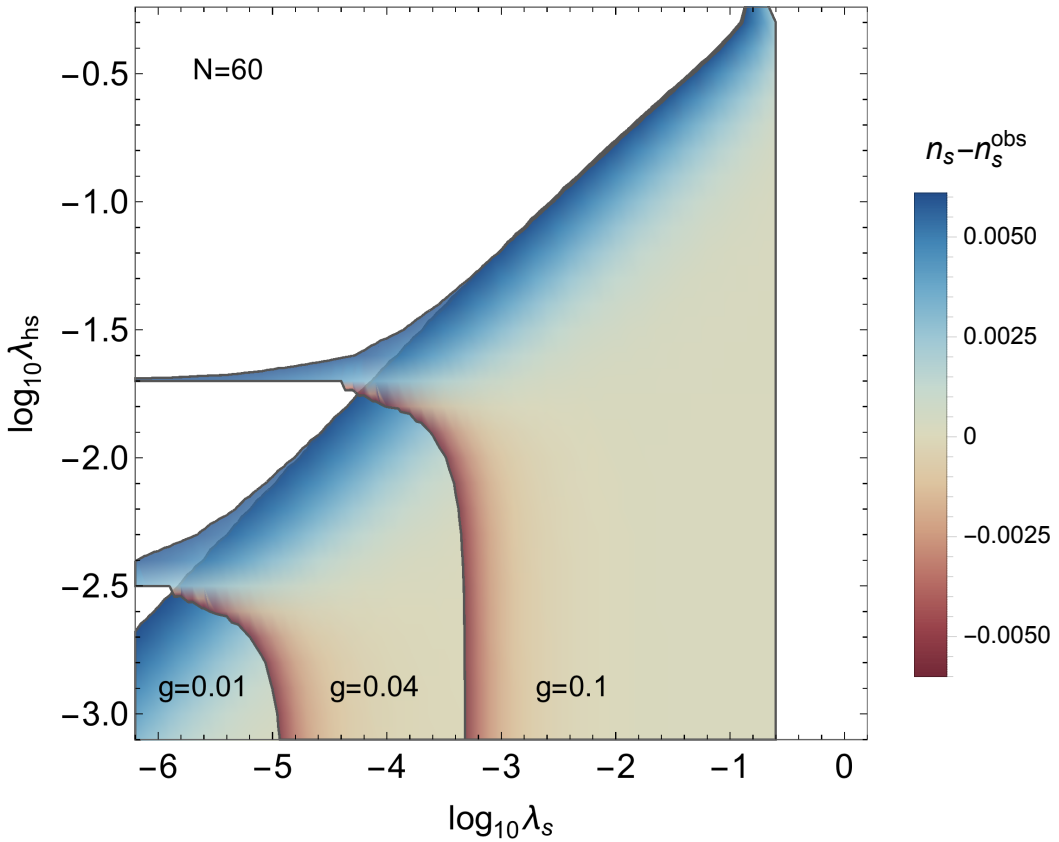
A Strong EWPT

- In this model a strong electroweak phase transition can be realized already at tree-level[2].
- 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.

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

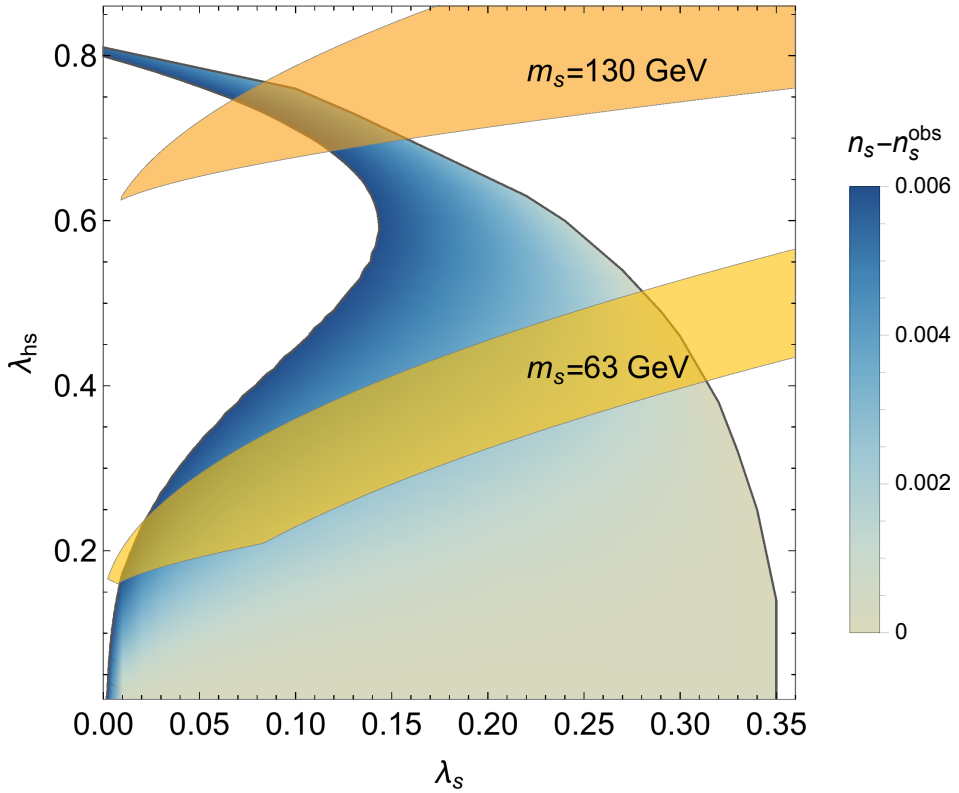
Starobinsky-like inflation

- At large fields values the Einstein frame potential is $U(\chi_s) \simeq \lambda_s M_P^4/\xi_s^2$.
- Quantum corrections affect predictions for inflationary observables $\mathcal{P}_\zeta$, n_s, and r.



A Strong EWPT: Z_2–symmetric potential

- Dynamics can be studied analytically. If s is stable, it's properties are strongly constrained by DM overclosure and LHC constraints[3].

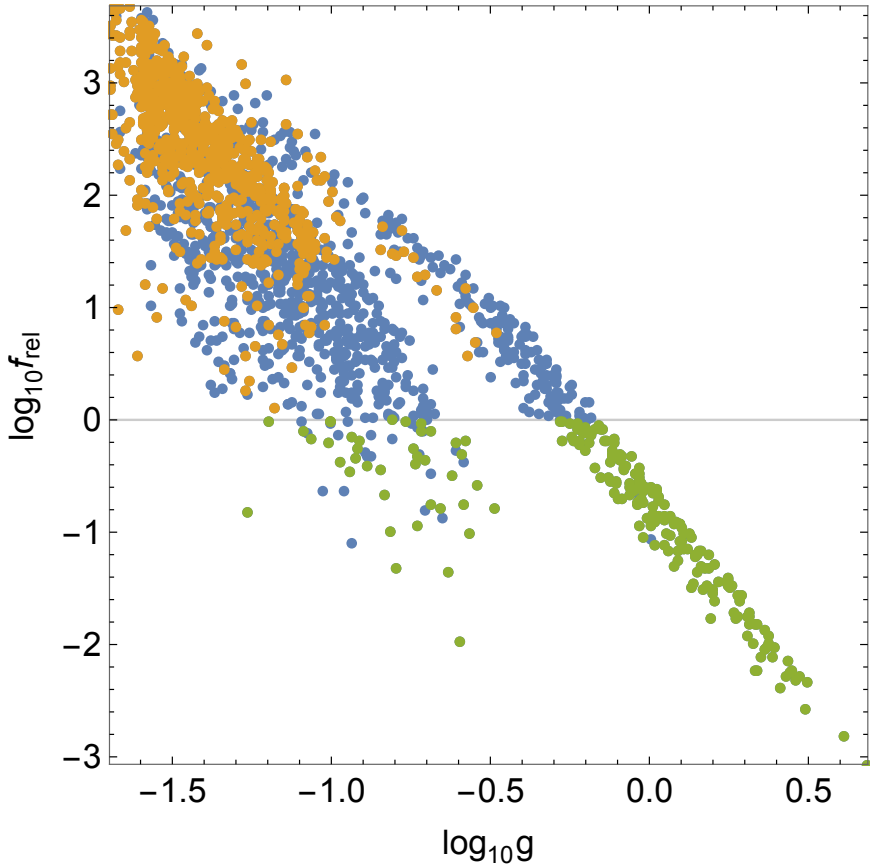


- The yellow and orange bands show where a Z_2–symmetric s gives a strong EWPT. Here $g = 0$.

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

A Strong EWPT: General potential

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



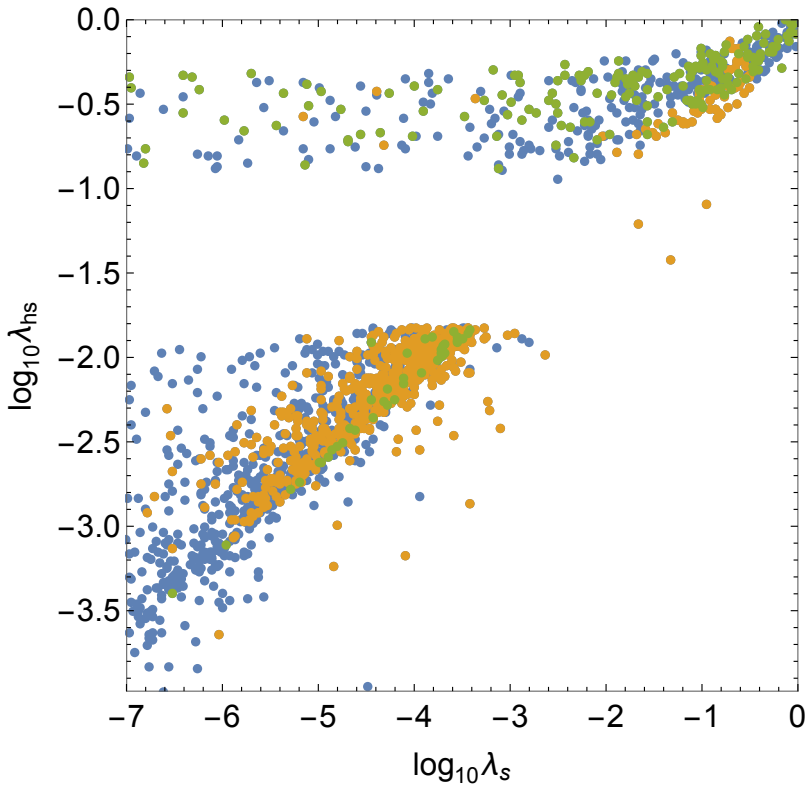
- All points give a strong EWPT and are compatible with the LHC data. Orange points give successful inflation and green points are in agreement with the LUX constraints.

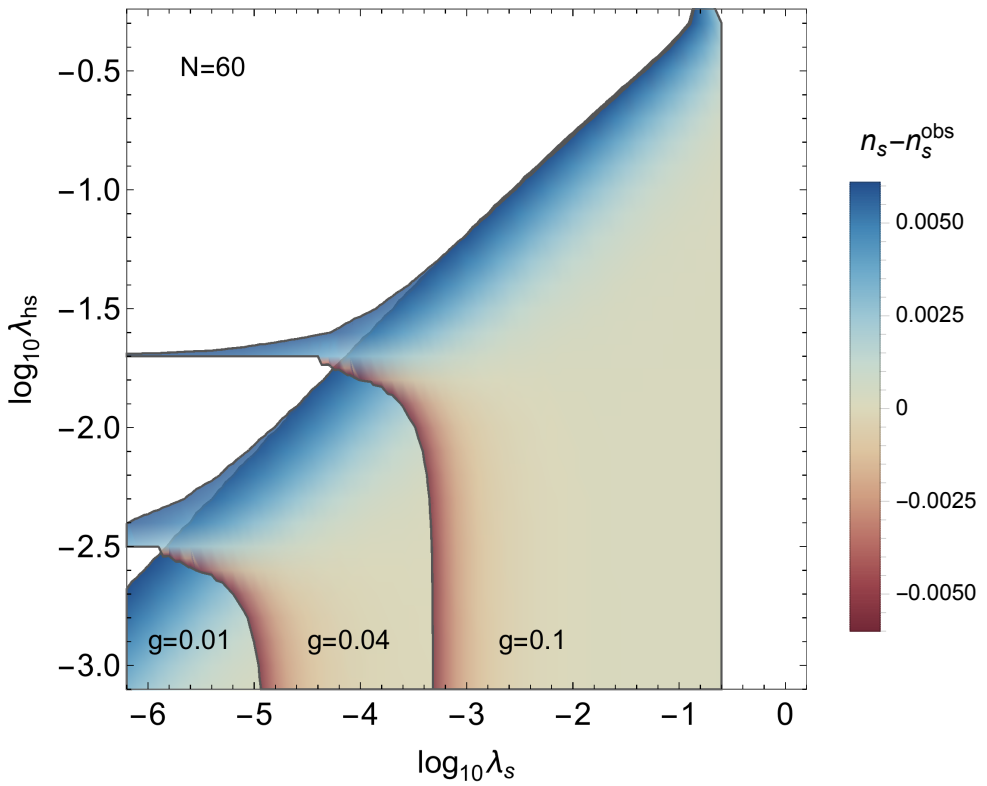
Active–sterile neutrino mixing

- 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: the mixing with the active neutrinos opens a decay channel for the singlet fermion.
- To alleviate the overclosure constraint we require ψ to decay before the big bang nucleosynthesis at $T \simeq 1$ MeV.
- This requires $\sin^2\theta \gtrsim 10^{-11}$ (Z boson decay requires $\sin^2\theta \lesssim 0.007$).

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.





Conclusions

- 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 from inflationary dynamics by studying in detail phase transitions in the early universe.