On the dark radiation problem in the axiverse

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Outline

1. Inflation
2. Light scalars
3. Dark radiation
   - R^2-inflation
   - Non-minimal kinetic terms
   - Non-milimal couplings to gravity

Slow roll inflation

Before the hot Big Bang:

$$a(t) = a_0\, e^{Ht}, \;\; H \approx \mathrm{const}$$

$$S = \int d^4x \sqrt{-g} - \frac{M_P^2}{2} R + \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi)$$

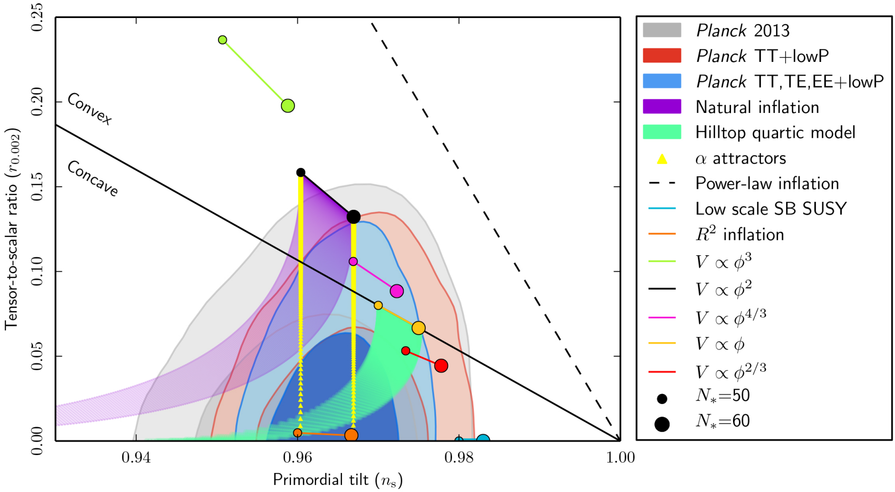
The inflaton perturbations are seeds for the CMB anisotropy and all structures in the late Universe

$$\langle \delta\phi^2 \rangle = \int \frac{dk}{k} P(k), \;\; \langle \phi^2 \rangle \sim 10^{-10}$$

The most important Planck observables:

- $r = \frac{P_T}{P_s}$ – tensor to scalar ratio
- $P_s \sim k^{n_s - 1}$ –tilt of the spectrum of scalar perturbations

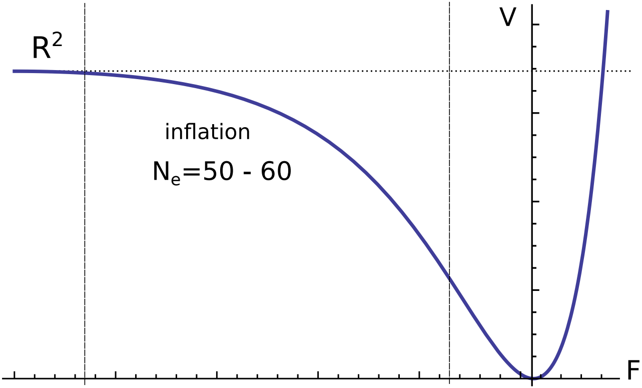
Inflationary parameters



How should the inflaton potential look like?

For R^2-inflation

$$V(\phi) = \frac{3\mu^2 M_P^2}{4}\left(1 - e^{-\sqrt{2/3}\phi/M_P}\right)^2$$



Ways to obtain the flat potential

- Inflaton from the gravity sector (R^2-inflation)
- Non-minimal coupling to gravity ($R\phi^2$, $R\phi$, $\dots$)
- Non-minimal kinetic term for the inflaton (α-attractors)
- ...

All these models are non-renormalizable.

They can be treated only as effective theories

Light scalars possessing a perturbative shift symmetry

$$a \to a + \mathrm{const}$$

Models:

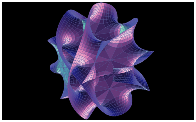
- dilaton
- QCD axion (solution for the strong CP problem)
- Nambu-Goldstone bosons of some broken global symmetries
- axion-like particles
- string axions

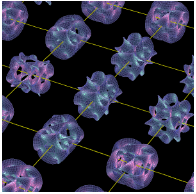
ALPs and string landscape

ALPs and string landscape

Axiverse

- String scenarios generically predict many axions posessing a perturbative shift symmetry
- Each axion corresponds to a cycle in a compactification manifold
- Likely, the number of string axions is about 100
- One of them can play the role of QCD axion
- In order not to spoil the axion solution for CP problem in QCD, other axions should have the coupling scale $F_a \sim 10^{16}$ GeV
- Masses of axions are distributed homogeneously in the logariphmic scale





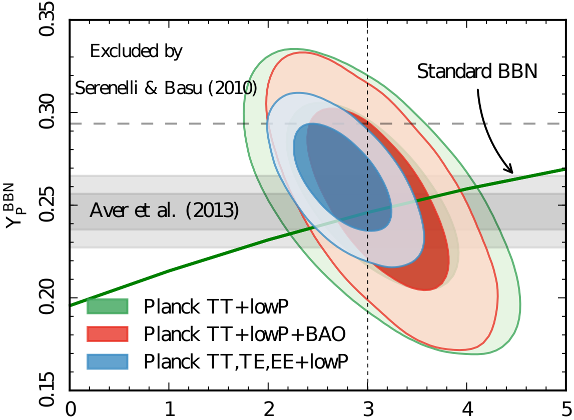
Svrcek, Witten, 2006

Arvanitaki, Dimopoulos, Dubovsky et al., 2009

Planck bounds on the dark radiation

The amount of the dark radiation is measured in the number of relativistic degrees of freedom (neutrinos) N_{eff}

$$N_{eff} = 3.15 \pm 0.23.$$



Production of the dark radiation

Assume: after inflation the Universe reheats due to the production of the SM particles (rate Γ_{SM}). In general, some amount of axions can also be created (rate Γ_a).

$$\Delta N_{\text{eff}} = N \frac{g_{\text{reh}}}{g_\nu} \left(\frac{g_{\text{BBN}}}{g_{\text{reh}}} \right)^{4/3} \frac{\Gamma_a}{\Gamma_{SM}}$$

$g_\nu = 2 \cdot 7/8$, for the SM $g_{\text{reh}} = 106.75$, $g_{\text{BBN}} = 10.75$.

Observation:

If the reheating happens due to some universal mechanism, i. e. $\Gamma_{SM} \sim \Gamma_a$, one obtains

$$\Delta N_{\text{eff}} \sim 0.7\, N$$

The Starobinsky model

$$S = -\frac{M_{\mathrm{P}}^2}{2}\int\sqrt{-g}\; d^4x\left[R - \frac{R^2}{6\,m^2}\right] + S_{\mathrm{matter}} + S_a$$

$$S_H = \int d^4x\sqrt{-g}\left(\xi_h R\,(H^\dagger H) + |D^\mu H|^2 - V_{SM}(H^\dagger H)\right),\quad S_a = \int d^4x\sqrt{-g}\sum_i \frac{1}{2}(\partial_\mu a_i)^2$$

$$g_{\mu\nu} \to e^{\sqrt{2/3}\,\phi/M_{\mathrm{P}}}\, g_{\mu\nu} \quad \Rightarrow$$

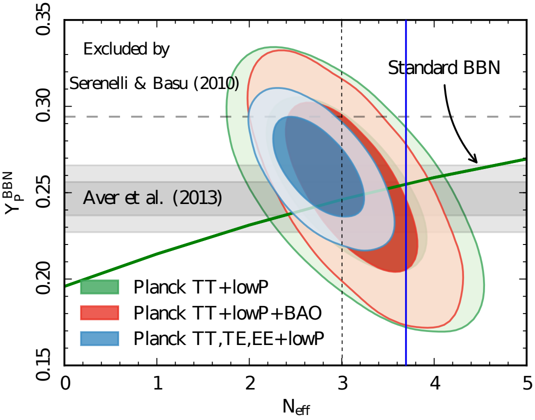
$$S_{EF} = \int\sqrt{-g}\; d^4x\left[-\frac{M_{\mathrm{P}}^2}{2}R + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right] + S_{matter} + S_a + S_{int}$$

$$S_{int} = -\int d^4x\sqrt{-g}\left(\frac{(1+6\xi_h)\,\phi}{\sqrt{6}M_P}D_\mu H^\dagger D^\mu H + \sum_i \frac{\phi}{\sqrt{6}M_P}(\partial_\mu a_i)^2\right)$$

$$\boxed{\Gamma_{\mathrm{SM}} = \frac{m^3(1+6\xi_h)^2}{48\pi\,M_{\mathrm{P}}^2},\quad \Gamma_{\mathrm{a}} = \frac{m^3}{192\pi M_{\mathrm{P}}^2} \quad\Rightarrow\quad \Delta N_{eff} = \frac{0.7N}{(1+6\xi_h)^2}}$$

The Starobinsky model: extra scalar is in tension with Planck

$$\Delta N_{eff} = \frac{0.7N}{(1+6\xi_h)^2}$$



Inflation driven by non-minimal kinetic terms

$$L = \frac{c}{s^2}(\partial_\mu s)^2 - \mu^2(s-s_0)^2 + V_1(s-s_0)$$

How can this lagrangian for the inflaton appear?

- String moduli (the dark radiation problem was first discussed in Cicoli, Conlon, Quevedo, 2012)
- No-scale supergravity (Ellis, Nanopoulos, Olive, 2013)
- α-attractors (Linde, Kallosh, 2013)
- ...

After the canonical normalization:

$$S = \int d^4x\sqrt{-g}\left(\frac{(\partial_\mu\phi)^2}{2} - V(\phi)\right),$$

General expansions

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{(\partial_\mu\phi)^2}{2} + \sum_{i=1}^{N} f_i(\phi)\frac{(\partial_\mu a_i)^2}{2} - V(\phi)\right),$$

The most relevant interactions with the SM:

$$S_{int} = \int d^4x\sqrt{-g}\left(y(\phi)|D_\mu\mathcal{H}|^2 - \frac{1}{4}g_j(\phi)F_{\mu\nu,j}F_j^{\mu\nu} + z_i(\phi)\bar{\psi}_i\gamma^\mu D_\mu\psi_i\right).$$

In effective theory we might expect the expansions suppressed by some scale $\Lambda \lesssim M_P$:

$$f_i(\phi) = 1 + \beta_i\frac{\phi}{\Lambda} + \gamma_i\frac{\phi^2}{\Lambda^2} + \ldots,$$
$$g_i(\phi) = 1 + \delta_i\frac{\phi}{\Lambda} + \ldots, \quad y(\phi) = 1 + \gamma\frac{\phi}{\Lambda} + \ldots.$$

Amount of the dark radiation

In the presence of axions, the inflaton must couple to matter significantly stronger than to the axions. In the general case this is parametrized by the reheating temperature:

$$\Gamma_{\rm SM} \simeq 3\frac{T_{\rm reh}^2}{\sqrt{g_{\rm reh}}M_{\rm P}}\,, \quad \Gamma_a = \frac{\beta^2 m^3}{128\pi\Lambda^2}$$

$$\Delta N_{\rm eff} = 0.024\, N\, \frac{\beta^2 m^3 M_{\rm P}}{\Lambda^2 T_{\rm reh}^2}$$

Assumptions:

- Inflaton perturbatively decays to axions, i. e. linear term $\phi(\partial_\mu a)^2/\Lambda$ is not forbidden by some symmetry
- Reheating happens due to the inflaton decay

Inflation driven by non-minimal coupling to gravity

Non-minimal coupling to gravity allows for exponentially flat potential.

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2+\xi\phi^2}{2}R + \frac{(\partial^\mu\phi)^2}{2} - \frac{\lambda\phi^4}{4}\right)$$

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\ , \quad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2} \quad \Rightarrow$$

$$S_{EF} = \int d^4x\sqrt{-\hat{g}}\left\{-\frac{M_P^2}{2}\hat{R} + \frac{(\partial^\mu\chi)^2}{2} - U(\chi)\right\}$$

$$L_a = \frac{1}{2}\Omega^2(\partial_\mu a)^2 = \frac{1}{2}\left(1+\frac{\xi\phi^2}{M_P^2}\right)(\partial_\mu a)^2.$$

Notice: $\phi \to -\phi$ symmetry and the absence of linear term

Large and small coupling

- $\xi \gg 1$, SM Higgs inflation (Bezrukov, Shaposhnikov, 2008)

$$\phi > M_P/\sqrt{\xi}, \quad U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$

After inflation: harmonic oscillations with $\omega = \sqrt{\lambda/3}M_P/\xi$

$$L_{int} = \frac{\chi}{\sqrt{6}M_P}\,\partial_\mu a\,\partial^\mu a$$

- $\xi \ll 1$, light inflaton (Bezrukov, Gorbunov, 2013)

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\tanh^4\left(\frac{\sqrt{\xi}\chi}{M_P}\right), \quad L_{int} = \xi\,\frac{\chi^2}{M_P^2}\partial_\mu a\,\partial^\mu a\,.$$

The axion production is strongly suppressed $(1/M_P^2)$

Dark radiation in Higgs inflation

$$T_{\rm reh} \simeq 6 \times 10^{13} \text{ GeV}$$

N axions contribute to the dark radiation as

$$\Delta N_{\rm eff} \simeq 5.6 \times 10^{-8}\, N \left(\frac{\omega}{1.3 \times 10^{-5} M_{\rm P}} \right)^3 \left(\frac{6 \times 10^{13}}{T_{\rm reh}} \right)^2$$

The production is inefficient because of fast reheating

⋆ If the axion(s) have additional less suppressed couplings to the SM fields (photons) they can be produced thermally

⋆ QCD-axion with $f_a \sim 10^{10} - 10^{12}$ GeV thermalizes in plasma with $T > 10^9$ GeV providing with

$$\boxed{\Delta N_{eff} = 0.026}$$

Observable in future experiments!

Conclusions

- Particular inflationary models might be incompatible with the presence of extra light scalars because of overproduction of the dark radiation
- This can not happen only if the inflaton couples to the SM much stronger than to extra scalars
- In terms of the reheating temperature, $T_{reh} \gtrsim 10^9$ GeV if the axion coupling to the inflaton is suppressed by Planck mass (natural to expect)
- Axiverse is still compatible with the models of inflation which is followed by the efficient reheating (as in Higgs inflation), or if the inflaton decay to axions is forbidden by some symmetry

Thanks for your attention!