Universal Constraints on Axions From Inflation

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Motivation

- Axion-like particles are pseudo-Goldstone bosons of a broken symmetry. They appear in different contexts (CP problem, String Theory, BSM, etc.).

- Inflation: protection mechanism for inflaton potential in large field models (Natural Inflation: Shift symmetry broken to a discrete symmetry) [Freese, Frieman and Olinto '90]

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] \qquad f \equiv \text{axion decay constant}$$

Observations require the decay constant (f) to be superPlanckian. Ways-out (Kim-Nilles-Peloso mechanism, N-flation, Axion Monodromy).

- After symmetry breaking $\rightarrow$ axial coupling is allowed by symmetries

$$\mathcal{L}_{\text{int}} = -\frac{\alpha\phi}{4f} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a, \qquad \alpha \equiv \text{dimensionless coefficient}$$

Axial Coupling with gauge fields

- We consider the case of a coupling to a $U(1)$ gauge field (A_μ).
- Eq. of motion in the basis of circular polarization vectors $(\vec{e}_\pm)$ is [Anber and Sorbo 06']

$$A_\pm(\tau,k)'' + \left(k^2 \pm \frac{2k\xi}{\tau}\right) A_\pm(\tau,k) = 0, \quad \xi \equiv \frac{\alpha\dot{\phi}}{2fH} = \frac{\alpha M_p}{f}\sqrt{\frac{\epsilon_\phi}{2}} \simeq const.$$

  Tachyonic enhancement of one polarization around the time of horizon crossing of a given mode $((8\xi)^{-1} \lesssim -k\tau \lesssim 2\xi)$.

- If the axion is the inflaton there is a new coupling stronger than gravitational between adiabatic curvature perturbation $(\mathcal{R} \simeq H\frac{\delta\phi}{\dot{\phi}})$ and gauge-fields

  [Anber and Sorbo 06', Barnaby and Peloso 11']

$$\mathcal{L}_{\text{int}} = -\frac{\alpha\delta\phi}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad \mathcal{L}_{\text{int}}^{\text{scalar}} = 2\xi\mathcal{R}\,\vec{E}\cdot\vec{B}, \qquad F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\vec{E}\cdot\vec{B}.\ .$$

- No new interaction with tensor perturbations (h_{ij}), beside $\mathcal{L}_{\text{int}}^{\text{tensor}} = (T_{ij}^{\text{EM}})^{TT} h^{ij}$.

Anisotropies - Axion as the inflaton

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- Corrections to the Power Spectrum (γ_α are just numerical coefficients)

  [Sorbo 11', Barnaby and Peloso 11']

$$P_{\mathcal{R}} \simeq \mathcal{P}\left(1 + \gamma_s \frac{\mathcal{P}}{\xi^6} e^{4\pi\xi}\right), \qquad \mathcal{P}^{1/2} = \frac{H^2}{2\pi\dot{\phi}}$$

$$P_{\text{GW}} \simeq 16\epsilon\mathcal{P}\left(1 + \gamma_t \frac{\epsilon\mathcal{P}}{\xi^6} e^{4\pi\xi}\right);$$

- 3-point function peaks on equilateral configurations $(k_1 = k_2 = k_3)$

  [Planck '13, Barnaby et al. 11', Meerburg & Pajer 12', Linde et al. 12'] :

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle^{\text{one-loop}} = (2\pi)^3 \delta^{(3)}\left(\sum_i \vec{k}_i\right) f(k_1, k_2, k_3) \frac{\mathcal{P}^3}{\xi^9} e^{6\pi\xi};$$

$$f_{NL}^{\text{equi}} = \gamma_{NG} \frac{\mathcal{P}^3}{\mathcal{P}_{\mathcal{R}}^2 \xi^9} e^{6\pi\xi} < -42 \pm 75 \quad \Rightarrow \quad \xi \lesssim 2.5 \Leftrightarrow f \gtrsim \frac{\alpha}{6} \frac{\dot{\phi}}{H} M_p$$

Axion **Not** the inflaton

Can we avoid these constraints if the axion is not the inflaton but some other pseudo-scalar (σ), irrelevant for the inflationary evolution?

[Barnaby et al. 12', Shiraishi et al., Cook & Sorbo 13', Mukohyama et al., **RZF** & Sloth 14']

$$\mathcal{L}_{\text{int}} = -\frac{\alpha\sigma}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- There is no direct interaction with the inflaton, beside the gravitational coupling, so adiabatic curvature perturbations might be suppressed.
- Tensor production is unaffected because $T^{\text{EM}}_{\mu\nu}$ remains the same. Proposed as a mechanism for generating GW larger than the vacuum.
- Very relevant because then the observation of tensor modes would not tell us directly the energy scale of inflation.

- Problem: $\delta\sigma$ is not a gauge invariant quantity. What happens when we rewrite the interaction in terms of gauge invariant quantities?

- E.g, in the spatially flat gauge the axion fluctuations are

$$\delta\sigma = \frac{\dot{\sigma}}{H}\left(\mathcal{S}_{\sigma\phi} + \mathcal{R}\right), \qquad \mathcal{S}_{\sigma\phi} = H\left(\frac{\delta\sigma}{\dot{\sigma}} - \frac{\delta\phi}{\dot{\phi}}\right).$$

  where $\mathcal{S}_{\sigma\phi}$ is the gauge-invariant isocurvature perturbation (orthogonal to $\mathcal{R}$). The same result can be derived in any other gauge.

- Gauge fields couple universally to ($\mathcal{R}$) with a strength ξ, independent of the role of the axion. $\mathcal{R}$ and $\mathcal{S}_{\sigma\phi}$ are equally generated at horizon crossing;

- If the axion does not decay during inflation the constraints on ξ remain the same and therefore, this mechanism cannot, generically, generate larger than the vacuum.

Superhorizon Evolution of Curvature Perturbations

Special case: Axion becomes massive and decays during inflation [Mukohyama et al. 14']

- Curvature and isocurvature perturbation cancel each other:

$$\delta\sigma \to 0 \quad \Rightarrow \quad \mathcal{R} + \mathcal{S}_{\sigma\phi} \to 0$$

Are non-gaussianities completely erased in this case?

The gravitational coupling between the inflaton and the axion induces an extra enhancement of curvature perturbations $\mathcal{R}$ at superhorizon scales [Linde et al. 04']

$$\mathcal{R}(\tau_f) \simeq \mathcal{R}_\phi = \mathcal{R}_\phi^* - \int_{\tau_*}^{\tau_f} \left(\frac{\dot{\sigma}}{\dot{\phi}}\right)^2 \mathcal{R}'_\sigma \, d\tau. \quad * \equiv \text{horizon crossing}$$

To compute $\mathcal{R}'_\sigma$ we need to solve the system of equations of motion for $\delta\phi$ and $\delta\sigma$ coupled gravitationally: [Sasaki 86', Mukhanov 88]

$$\delta\ddot{\phi}_I + 3H\delta\dot{\phi}_I + \frac{k^2}{a^2}\delta\phi_I + \sum_J \left[V_{IJ} - \frac{1}{a^3}\frac{d}{dt}\left(\frac{a^3}{H}\dot{\phi}_I\dot{\phi}_J\right)\right]\delta\phi_J = \begin{pmatrix} 0 \\ \frac{\alpha}{f}\vec{E}\cdot\vec{B} \end{pmatrix}.$$

- Putting everything together we finally get [**RZF**, Sloth 14']

$$\mathcal{R}(\tau_f) = \mathcal{R}_\phi^* + \left(\frac{\dot{\sigma}_*}{\dot{\phi}_*}\right)^2 \mathcal{R}_\sigma^* \left[\Delta N \left(2\epsilon_\phi - \lambda_2\right) + \frac{\epsilon_\phi}{6}\right]$$

  where $\Delta N = \log\left(\tau^*/\tau_{osc}\right)$ is the duration in e-folds from horizon crossing until the decay of the axion.

  This superhorizon enhancement is ϵ suppressed compared to the direct sourcing at horizon crossing however it is still $\propto \Delta N$.

- Scalar Power Spectrum: $P_\mathcal{R} \simeq \mathcal{P}\left(1 + \gamma_s\, \Delta N^2 \epsilon^2 \frac{\mathcal{P}}{\xi^6} e^{4\pi\xi}\right)$
  If $\Delta N > 2.2$ the non-gaussian contribution to the power spectrum is larger than the tensor spectrum and so we would expect to observe first non-gaussianities.

Overall results [RZF, Sloth 14']

- Non-Gaussian parameter: $f_{\mathsf{NL},\sigma}^{\mathsf{eq}} \simeq \epsilon^3 \Delta N^3 \gamma_{NG} \frac{\mathcal{P}^3}{\left(P_\zeta^{\mathsf{obs}}\right)^2} \frac{e^{6\pi\xi}}{\xi^9}$

  The generation of GW remains unchanged so the non-gaussian constraints imply a tensor to scalar ratio (r)

$$r = \frac{P_{\rm GW}}{P_{\mathcal{R}}} < \frac{10^{-2}}{\Delta N^2} \left(f_{\mathsf{NL}}^{\mathsf{eq}}\right)^{2/3} .$$

  A large (observable) value of r, generated by this mechanism, is only possible if the axion decays right after the largest scales left the horizon. Even if the perturbations are generated by the curvaton the same conclusion holds.

Conclusions

- The presence of axion-like particles is very natural in many frameworks, for instance for realizations of large field models of inflation.

- The presence of an axial coupling with $U(1)$ gauge fields during inflation has been studied in the past years. It leads to a tachyonic enhancement of the gauge fields and a new universal coupling to adiabatic curvature perturbation, independently of the role of the axion during inflation.

- The generation of anisotropies puts a lower bound on the axion decay constant $f_i \gtrsim \frac{\alpha_i}{6} \frac{\dot{\phi}_i}{H} M_p$. This can be relevant for extensions of Natural Inflation where more than one axion is required.

- Proposed models to generate large GW on large scales by such a mechanism become very much constrained and need the axion to become massive and decay, quickly after horizon crossing of the largest scales.