Gauge and fermion preheating & the end of axion inflation

Evangelos Sfakianakis

University of Illinois at Urbana-Champaign

APS Meeting, Division of Particles and Fields, 2015

Axion inflation

BICEP suggests $r \lesssim 0.1$. Large r values need super-Planckian field excursions (Turner-Lyth bound)

Shift symmetry $\phi \to \phi + c$ protects inflation from UV physics.

Shift symmetry makes inflation impossible, so it has to be broken (softly).
Examples include

- Chaotic inflation: $V(\phi) = \frac{1}{2} m^2 \phi^2$
- Natural inflation: $V(\phi) = \mu^4 \left(1 - \cos(\phi/f)\right)$
- Axion monodromy: $V(\phi) = \mu^3 \left(\sqrt{\phi^2 + \phi_c^2} - \phi_c \right)$

Allowed couplings

A field with a shift symmetry can only couple derivatively to other degrees of freedom

$$\mathcal{L}_{\rm Int} \subset \frac{\alpha}{8f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} + \frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi$$

$$\updownarrow$$

$$-\frac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu\partial_\alpha A_\beta$$

From a EFT perspective, we expect these interactions to be present.

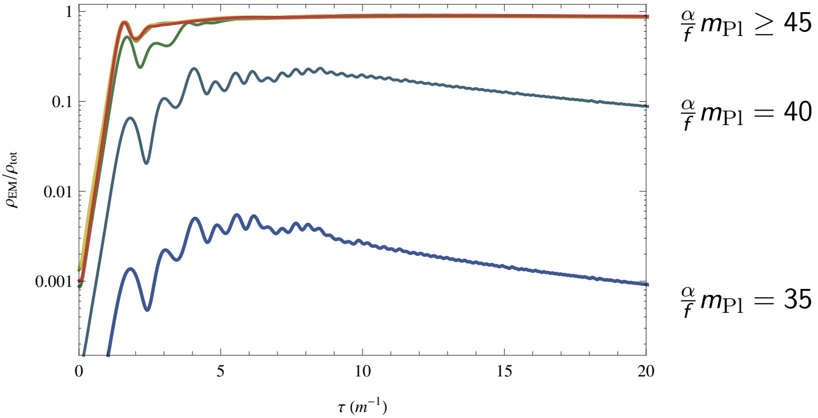
Gauge Fields

$$\boxed{\mathcal{L}_{\text{Int}} = -\frac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu \partial_\alpha A_\beta}$$

A detailed analysis can be found in:
P. Adshead, J. T. Giblin, T. R. Scully and E. I. S., arXiv:1502.06506 [astro-ph.CO]

Gauge Fields

Coupling the axion to gauge fields can lead to explosive transfer of energy from the inflaton.



Reheating can occur after a single axion oscillation for $\frac{\alpha}{f} m_{\rm Pl} \geq 45$.

Fermion Fields

$$\boxed{\mathcal{L}_{\text{Int}} = \frac{C}{f}\partial_\mu \phi \bar{\psi}\gamma_5 \gamma^\mu \psi}$$

A detailed analysis can be found in:

P. Adshead, and E. I. S., arXiv:1508.00881 [hep-ph]

P. Adshead, and E. I. S., arXiv:1508.00891 [hep-ph]

Model set-up

We consider a pair of Majorana fermions coupled to the inflaton, studying only left-handed ones

$$i\left(\partial_t - i\left(\frac{k}{a}\lambda + \frac{C}{f}\dot{\phi}\right)\right)X_k^\lambda(t) = mY_k^{\lambda *}(t)$$
$$i\left(\partial_t + i\left(\frac{k}{a}\lambda + \frac{C}{f}\dot{\phi}\right)\right)Y_k^{\lambda *}(t) = mX_k^\lambda(t)$$

where X_k^λ and $Y_k^{\lambda *}$ are the rescaled fermion wave-functions, defined as

$$x^\lambda(t) = X_k^\lambda(t)\xi_\lambda(k)\ ,\ y^{\lambda\dagger}(t) = Y_k^{\lambda *}(t)\xi_\lambda(k)$$

where $x^\lambda, y^{\lambda\dagger}$ are two-component spinors and ξ_λ defines a basis of helicity eigenspinors $\vec{\sigma}\cdot\vec{k}\xi_\lambda = \lambda\xi_\lambda$ and

$$\tilde{k}_\lambda(t) = \frac{k}{a}\lambda + \frac{C}{f}\dot{\phi}$$

where the coupling term acts as a chemical potential.

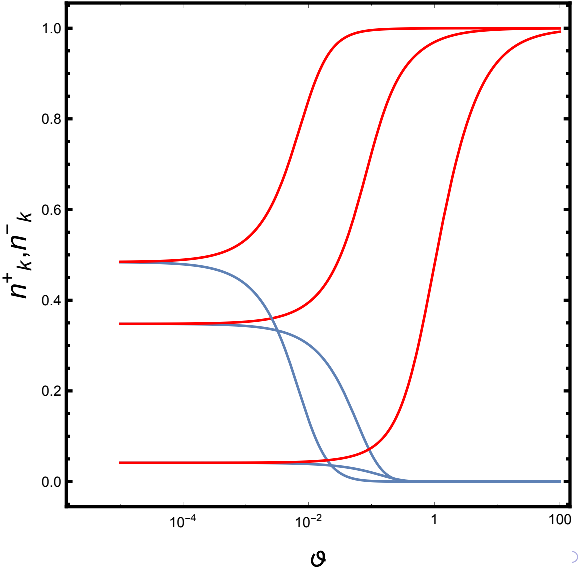
Particle Creation during Inflation

Positive helicity is favored by large values of $\vartheta = -\frac{C}{f}\frac{\dot{\phi}}{H}$.

$m/H = 0.01$

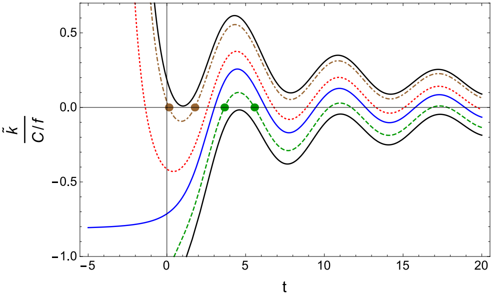
$m/H = 0.1$

$m/H = 0.5$



Non-adiabaticity

$$X_{ik}^{\lambda}(t) = A_{i\lambda}\sqrt{1+\frac{\tilde{k}_\lambda}{\omega_\lambda}}e^{i\int \omega_\lambda dt} + B_{i\lambda}\sqrt{1-\frac{\tilde{k}_\lambda}{\omega_\lambda}}e^{-i\int \omega_\lambda dt}$$

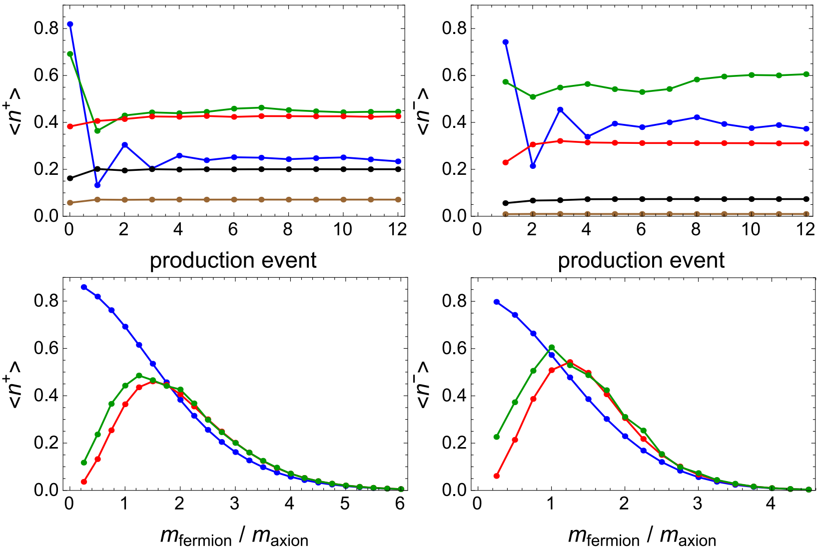


$$\tilde{k}_\lambda(t) = \frac{k}{a}\lambda + \frac{C}{f}\dot{\phi}$$

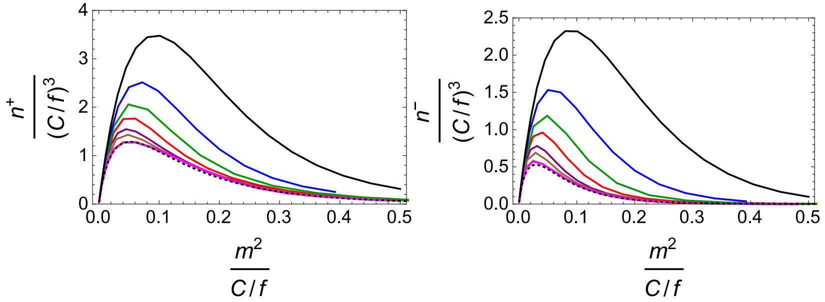
$$\omega_\lambda^2(t) = \tilde{k}_\lambda^2(t) + m^2$$

Every production event occurs within a Fermi sphere of $k^{\pm}_{\max} \sim \frac{C}{f}$ with strength $n_k = e^{-\pi \frac{m^2}{|dk/dt|_{t_*}}}$, where $\left|\frac{dk}{dt}\right|_{t_*} \sim \frac{C}{f}$.

Particle Creation after Inflation



Particle Production: Parameter Scan



$$n^{\pm} = \langle n^{\pm} \rangle (k^{\pm}_{\mathrm{max}})^3 = \langle n^{\pm} \rangle \left(\frac{k^{\pm}_{\mathrm{max}}}{C/f} \right)^3 (C/f)^3$$

$$\Delta n_{\mathrm{max}} = n^+ - n^- = \langle n \rangle \left[(k^+_{\mathrm{max}})^3 - (k^-_{\mathrm{max}})^3 \right] \approx 0.8 \left(\frac{C}{f} \right)^3$$

Helicity $\rightarrow$ Matter Asymmetry

During inflation, quantum effects can give the Higgs a VEV $\sim H$

We consider left-handed Standard Model neutrinos (and correspondingly heavy right-handed ones $\Leftrightarrow$ see-saw mechanism)

Helicity density asymmetry:

$$n_\nu^h = \sum_{\lambda=\pm 1} \int_0^{k^\pm_{\rm max}} dk\, k^2 \frac{3\lambda \langle n_\nu^\lambda(k)\rangle}{2\pi^2 a^3} \approx \frac{\langle n_\nu \rangle}{2\pi^2 a^3} \left(\frac{C\phi_0}{f} a_{\rm e} H_{\rm e} \right)^3$$

SM sphaleron can redistribute asymmetries $L \rightarrow B$

$$\boxed{\eta_{\rm R} \approx \frac{\langle n_\nu \rangle}{4\pi^2} \left(\frac{C\phi_0}{f} \right)^3 \frac{H_e}{M_{\rm Pl}} \frac{T_R}{M_{\rm Pl}}}$$

$\langle n_\nu \rangle \sim 0.2$, $H_e \sim 10^{-6} M_{\rm Pl}$, $T_R \sim 10^{13}\, GeV$, $f \sim 10^{-2} - 10^{-3} M_{\rm Pl}$
lead to $\boxed{\eta_R \sim 10^{-7} - 10^{-8}}$

Conclusions

- Gauge field preheating after axion inflation can be extremely efficient.
- Coupling to fermions leads to the asymmetric production of helicity states.
  - One helicity state is produced during inflation.
  - The other helicity state, which is produced only after inflation, is produced for a smaller range of wavenumbers.
  - The difference in the range of produced wavenumbers can lead to an asymmetric production
- The peak asymmetry has a very simple expression $\Delta n \sim \left(\frac{C}{f}\right)^3$.
- Helicity asymmetry in SM neutrinos can be converted to an observable baryon asymmetry through the sphaleron process.

Acknowledgments

I wish to thank my collaborators

- Peter Adshead (UIUC)
- John T. Giblin Jr (Kenyon College, Case Western Reserve U.)
- Timothy R. Scully (Kenyon College)

This work is supported in part by a Fortner Fellowship, awarded by the University of Illinois at Urbana-Champaign.

Thank you!