Gauge and fermion preheating
& the end of axion inflation

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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: $V(\phi) = \mu^4 (1 - \cos(\phi/f))$
- 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

\[ \mathcal{L}_{\text{Int}} \subset \frac{\alpha}{8f} \phi \epsilon_{\mu \nu \alpha \beta} F_{\mu \nu} F_{\alpha \beta} + \frac{C}{f} \partial_\mu \phi \bar{\psi} \gamma_5 \gamma^\mu \psi \]

\[ -\frac{\alpha}{f} \epsilon_{\mu \nu \alpha \beta} \partial_\mu \phi A_\nu \partial_\alpha A_\beta \]

From a EFT perspective, we expect these interactions to be present.
\[ \mathcal{L}_{\text{Int}} = -\frac{\alpha}{f} \epsilon_{\mu\nu\alpha\beta} \partial_\mu \phi A_\nu \partial_\alpha A_\beta \]

A detailed analysis can be found in:
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 $\frac{\alpha}{f} m_{Pl} \geq 45$. 

$\frac{\alpha}{f} m_{Pl} = 40$

$\frac{\alpha}{f} m_{Pl} = 35$
Fermion Fields

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

A detailed analysis can be found in:
Model set-up

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

\[ i \left( \partial_t - i \left( \frac{k}{a} \lambda + \frac{C}{f} \dot{\phi} \right) \right) X^\lambda_k(t) = m Y^\lambda*_{k}(t) \]

\[ i \left( \partial_t + i \left( \frac{k}{a} \lambda + \frac{C}{f} \dot{\phi} \right) \right) Y^\lambda*_{k}(t) = m X^\lambda_k(t) \]

where \( X^\lambda_k \) and \( Y^\lambda*_{k} \) are the rescaled fermion wave-functions, defined as

\[ x^\lambda(t) = X^\lambda_k(t) \xi_\lambda(k) \text{, } y^{\lambda\dagger}(t) = Y^\lambda*_{k}(t) \xi_\lambda(k) \]

where \( x^\lambda, y^{\lambda\dagger} \) are two-component spinors and \( \xi_\lambda \) 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 $\vartheta = -\frac{C \dot{\phi}}{f \dot{H}}$.

\begin{equation*}
m/H = 0.01
\end{equation*}
\begin{equation*}
m/H = 0.1
\end{equation*}
\begin{equation*}
m/H = 0.5
\end{equation*}
Non-adiabaticity

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

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

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

Every production event occurs within a Fermi sphere of \( k_{\text{max}}^\pm \sim \frac{C}{f} \)

with strength \( n_k = e^{-\frac{\pi m^2}{|dk/dt| t^*}} \), where \( \left| \frac{dk}{dt} \right|_{t^*} \sim \frac{C}{f} \).
Particle Production: Parameter Scan

\[ n^\pm = \langle n^\pm \rangle \left( k_{max}^\pm \right)^3 = \langle n^\pm \rangle \left( \frac{k_{max}}{C/f} \right)^3 (C/f)^3 \]

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

$$n_h^\nu = \sum_{\lambda=\pm1} \int_0^{k_{\text{max}}} dk \, k^2 \frac{3\lambda \langle n^\nu_\lambda(k) \rangle}{2\pi^2 a^3} \approx \frac{\langle n^\nu_\lambda(k) \rangle}{2\pi^2 a^3} \left( \frac{C\phi_0}{f} a e H_e \right)^3$$

SM sphaleron can redistribute asymmetries $L \rightarrow B$

$$\eta_R \sim \frac{\langle n^\nu \rangle}{4\pi^2} \left( \frac{C\phi_0}{f} \right)^3 \frac{H_e}{M_{\text{Pl}}} \frac{T_R}{M_{\text{Pl}}}$$

$$\langle n^\nu \rangle \sim 0.2, \quad H_e \sim 10^{-6} M_{\text{Pl}}, \quad T_R \sim 10^{13} \text{GeV}, \quad f \sim 10^{-2} - 10^{-3} M_{\text{Pl}}$$

lead to $\eta_R \sim 10^{-7} - 10^{-8}$
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 \( \Delta n \sim \left( \frac{C_f}{f} \right)^3 \).

- Helicity asymmetry in SM neutrinos can be converted to an observable baryon asymmetry through the sphaleron process.
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Thank you!

Questions