Signals from non-Abelian gauge fields coupled to axion during inflation

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Workshop on the non-Gaussian Universe

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Introduction: The strong CP problem

[Figs. from Hook 1812.0669]

- Why is the neutron electric dipole moment so small?

Naively, from the neutron size

\[ |d_n| \approx 10^{-13} \sqrt{1 - \cos \theta} \text{ e cm} \]

The current measurement is

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1. Any symmetry? $\rightarrow$ P, CP symmetries are broken in QCD.
   [Belavin et al 1975; ’t Hooft 1976]

2. Does the angle $\theta$ *dynamically* change? $\rightarrow$ QCD axion
   [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]
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The angle $\theta$ relaxes to 0 by the axion field.
Axion as Inflaton

[Freese, Frieman, Olinto 1990; Freese, Kinney 2004; Silverstein, Westphal 2008; Anber, Sorbo 2009; Barnaby, Peloso 2010; Germani, Kehagias 2011; Germani, YW 2011; Adshead, Wyman 2012; Dimastrogiovanni, Fasiello, Tolley 2012; …]

• Can QCD axion \((\phi = f \theta)\) also play a role of the inflaton?

  No, in the proposals.
  → Strong coupling scale \(\Lambda\) of QCD is too low \((\Lambda \sim 200\) MeV)

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V(\phi) = \Lambda_a^4 \left[ 1 - \cos \left( \frac{N_{DW} \phi}{f_a} \right) \right]
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1. Raise $\Lambda$ by introducing a new confining gauge field or UV instantons → requires a discrete symmetry or more axions

2. Drive inflation by kinetic terms of the axion
EFT of Axion below the PQ scale $f_a$

[Georgi, Kaplan, Randall 1986]

- Assuming $H < f_a$, the most general Lagrangian for the axion $\phi$ is (up to higher derivative terms):

$$
\mathcal{L}_a = -\frac{1}{2}(\partial \phi)^2 - \frac{1}{2} \text{Tr}(F_{\mu\nu} F^{\mu\nu}) - \frac{\lambda}{2 f_a} \phi \text{Tr}(F_{\mu\nu} \tilde{F}^{\mu\nu})
$$

+ deriv. coupled SM + “desert” or BSM

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$$X = -\frac{1}{2} (\partial \phi)^2$$

$$\mathcal{L}_a = c_1 X + \frac{c_2}{M^4} X^2 + \frac{c_3}{M^3} X \Box \phi + \frac{c_4}{M^2} G^\mu\nu \partial_\mu \phi \partial_\nu \phi$$

$$-\frac{1}{2} \mathrm{Tr}(F^\mu\nu F_{\mu\nu}) - \frac{\lambda}{2 f_a} \phi \mathrm{Tr}(F^\mu\nu \tilde{F}_{\mu\nu})$$

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• Invariant under $\phi \rightarrow \phi + \text{const.}$

• Field eqs. contain derivatives only up to 2nd order, i.e. no
  Ostrogradski ghost. [Deffayet et al 2011; Kobayashi et al 2011]
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Kinetically driven Axion Inflation

- In an FLRW background, EoM for axion $\phi$ & SU(2) gauge field $A$ are given by

$$A_0^a = 0, \quad A_i^a = \delta_i^a a(t)Q(t)$$

$$\ddot{Q} + 3H\dot{Q} + (\dot{H} + 2H^2)Q + 2g^2Q^3 = \frac{g\lambda}{f} \dot{\phi}Q^2$$
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  \[ \dot{J} + 3H J = -\frac{3g\lambda}{f} Q^2 (\dot{Q} + HQ) \]

  \[ \phi = \phi(t) \quad J \equiv c_1 \dot{\phi} + \frac{c_2}{M^4} \dot{\phi}^3 - 3 \frac{c_3 H}{M^3} \dot{\phi}^2 + 6 \frac{c_4 H^2}{M^2} \dot{\phi} \]

- In the absence of non-trivial gauge VEV, an attractor solution:

  \[ J \sim a^{-3} \rightarrow 0 \text{ with } \quad H = \text{const}, \quad \phi = \text{const} \]
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A_0^a = 0, \quad A_i^a = \delta_i^a a(t)Q(t) \quad \hat{\phi} = \text{const}
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$$A^a_0 = 0, \quad A^a_i = \delta^a_i a(t)Q(t) \quad \dot{\phi} = \text{const}$$

Gauge field

$$\ddot{Q} + 3H\dot{Q} + (\ddot{H} + 2H^2)Q + 2g^2Q^3 = \frac{g\lambda}{f} \phi Q^2$$

$$V_{\text{eff}}(Q) = H^2Q^2 + \frac{1}{2}g^2Q^4 - \frac{g\lambda}{3f} \phi Q^3$$

$$J_* = -\frac{g\lambda}{f}Q^3_\ast$$

Condition:

$$\left|\frac{\lambda}{f}\phi\right| > 4H$$
Scale dependence? How to end inflation?

- Invoke a shift symmetry breaking term in the kinetic sector as in k-Inflation, Galileon Inflation [Armendaritz-Picon et al 1999; Kobayashi et al 2010; Burrage et al 2010]

- Back-reaction from particle production may become important. [Anber, Sorbo 2009; Barnaby, Peloso 2011; Maleknejad, Komatsu 2018; Domcke, Ema, Mukaida, Sato 2018; Domcke, Sander 2019; Lozanov, Maleknejad, Komatsu 2018; Mirzagholi, Maleknejad, Lozanov 2019]

\[
\left[ \frac{\partial^2}{\partial \tau^2} + k^2 \pm \frac{2k\xi}{\tau} \right] A_{\pm}(\tau, k) = 0, \quad \xi = \frac{\lambda \phi}{2fH}
\]

\[
A_+(\tau, k) \approx \frac{1}{\sqrt{2k}} \left( \frac{k}{2\xi aH} \right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k/(aH)}} \quad \frac{\lambda}{f} \langle F_{\mu\nu} \tilde{F}^{\mu\nu} \rangle \sim 10^{-4} \frac{\lambda H^4}{f \xi^4} e^{2\pi\xi}
\]

\[
\dot{J} + 3HJ \approx -10^{-4} \frac{\lambda H^4}{f \xi^4} e^{2\pi\xi}
\]
Cosmological perturbations

• With SU(2) gauge field, one chirality of tensor modes grows large due to tachyonic instability. [Adshead et al 2012; Dimastrogiovanni, Peloso 2012; Dimastrogiovanni, Fasiello, Fujita 2016; Domcke, Sander 2019]

\[
\left[ \frac{\partial^2}{\partial \tau^2} + k^2 + \frac{2k\xi}{\tau} + 2 \left( \frac{\xi}{\tau^2} + \frac{k}{\tau} \right) \frac{gQ}{H} \right] t_{+2}(k, \tau) = 0
\]

• Non-Gaussian signals become interesting! [Agrawal, Fujita, Komatsu 2018]

• Instabilities in scalar modes? If \( Q < 2H/g \), there is an instability in scalar modes with canonical kinetic term.

• Higher derivative terms induce ghost or gradient instabilities? They can be avoided by choosing parameters, \( c_i \).
Concluding remarks

• The axion without potential can drive inflation with the non-canonical kinetic structure.

• A non-trivial VEV of SU(2) gauge field can be acquired during inflation.

• QCD axion may play a role of the inflaton. Even if it is a subdominant component, it may contribute to tensor modes due to tachyonic enhancement.