Role of QCD axion in an inflationary universe with non-Abelian gauge fields

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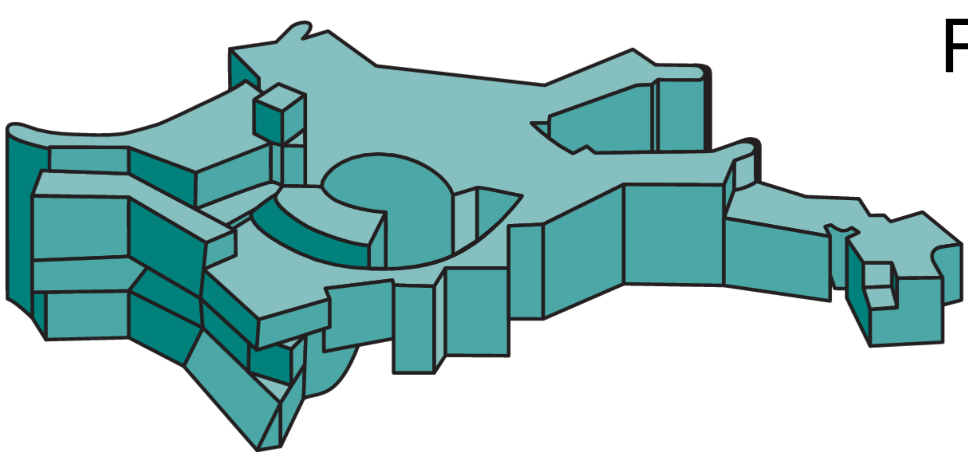
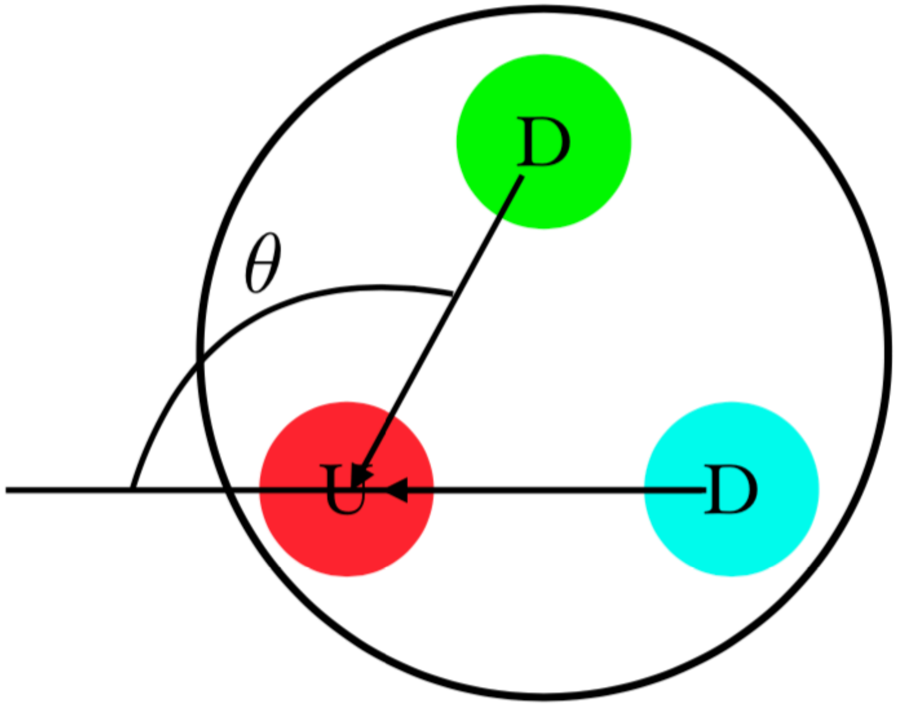


Introduction: The strong CP problem

[Figs. from Hook 1812.0669]

- Why is the neutron electric dipole moment so small?



Naively, from the neutron size

$$|d_n| \approx 10^{-13}\sqrt{1-\cos\theta}\, e\,\mathrm{cm}$$

The current measurement is

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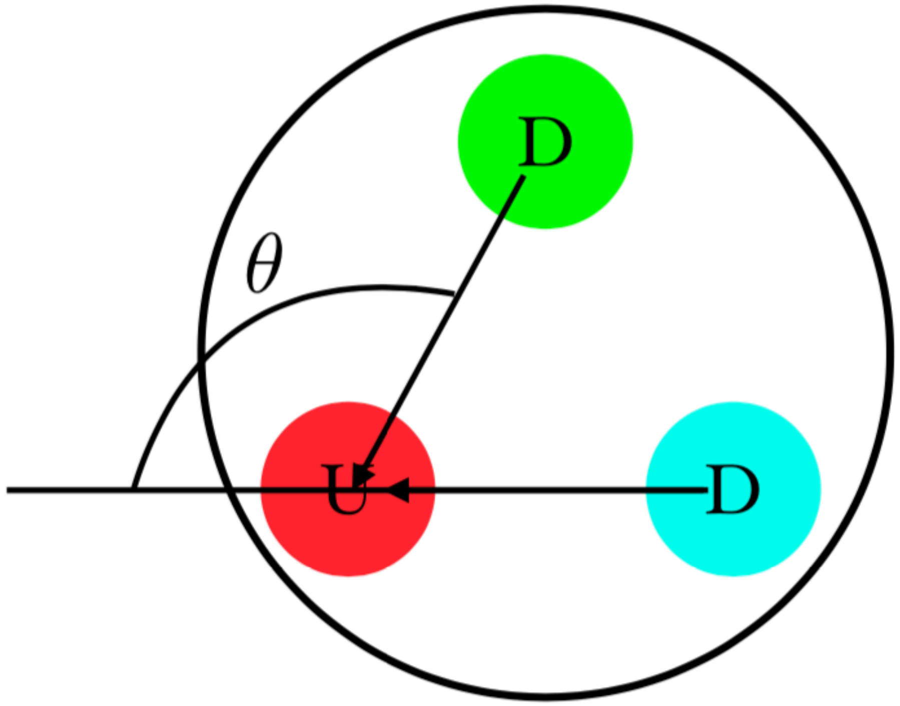

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1. Any symmetry? → P, CP symmetries are broken in QCD.
   [Belavin et al 1975; ’t Hooft 1976]

2. Does the angle θ *dynamically* change? → QCD axion
   [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]

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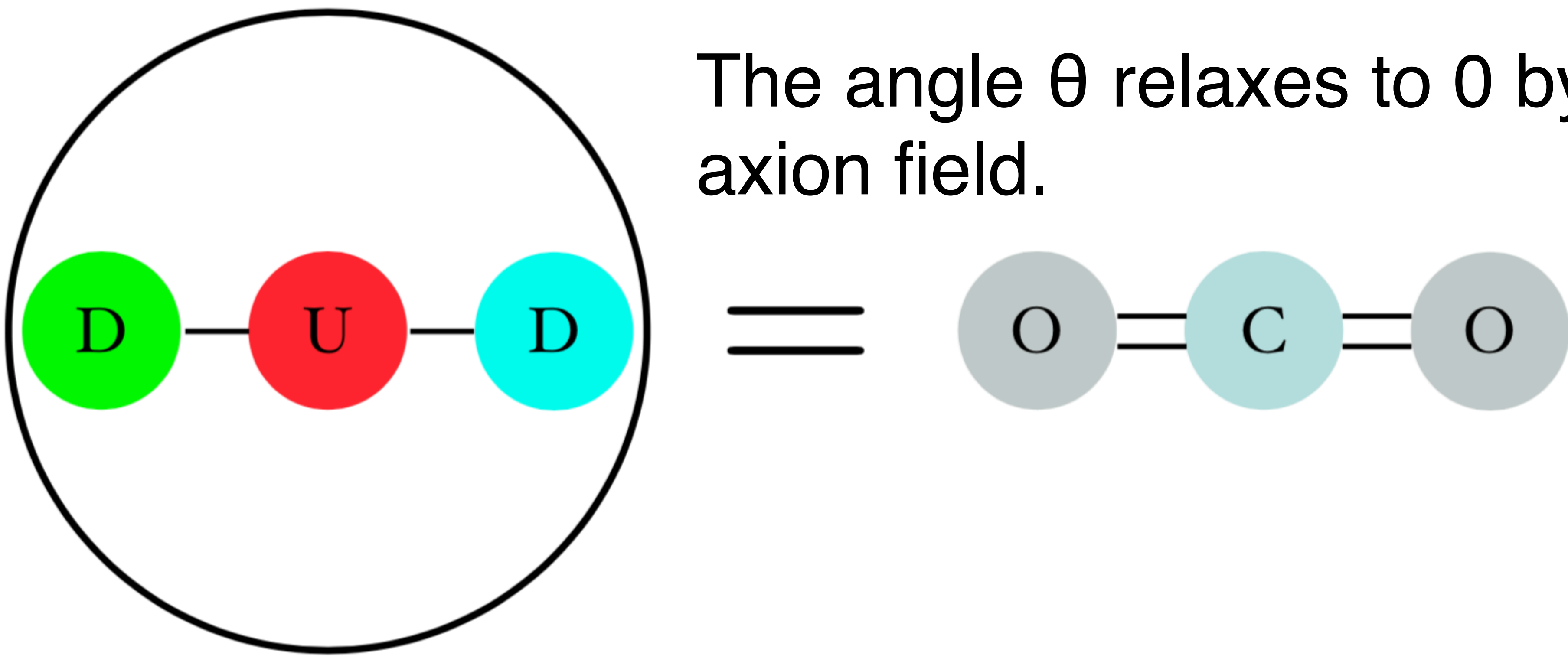

The angle θ relaxes to 0 by the axion field.

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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 Λ of QCD is too low (Λ ∼ 200 MeV)

$$V(\phi) = \Lambda_a^4 \left[1 - \cos\left(\frac{N_{\rm DW}\phi}{f_a}\right)\right]$$

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1. Raise Λ 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 $H < f$, the most general Lagrangian for the axion ϕ is (up to higher derivative terms):

$$\mathcal{L}_a = -\frac{1}{2}(\partial\phi)^2$$

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

+ deriv. coupled SM + "*desert*" or BSM

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

Galileon

Einstein tensor

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(non-)Abelian
Gauge fields

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Kinetically driven Axion Inflation

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

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

Gauge field

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

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Axion
$$\dot{J} + 3HJ = -\frac{3g\lambda}{f}Q^2(\dot{Q} + HQ)$$

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

- In the absence of non-trivial gauge VEV, an attractor solution: *J ~ a^(-3)* → *0* with *H = const,*

$$\boxed{\dot{\phi} = const}$$

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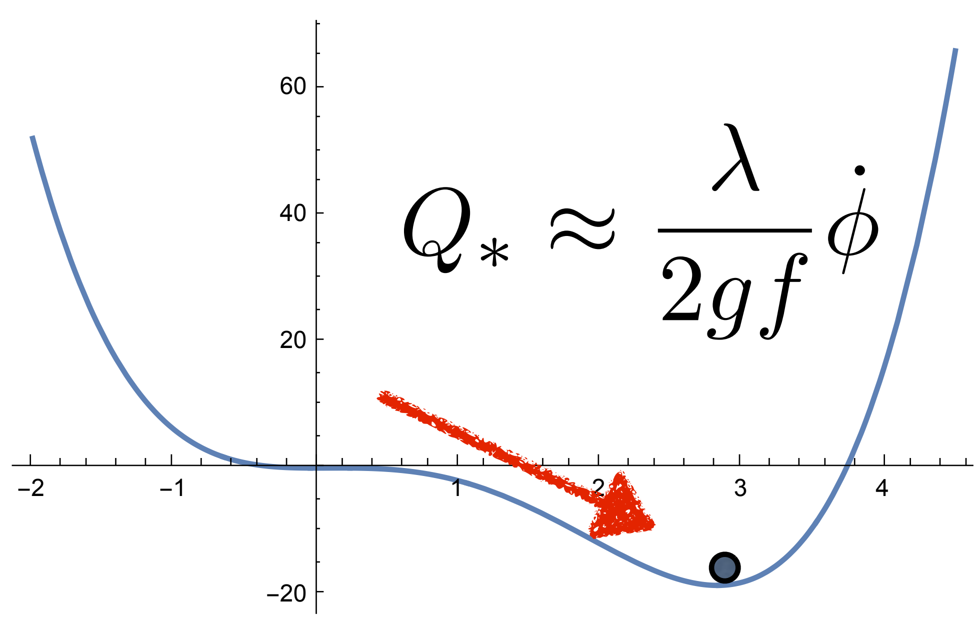
$$V_{\rm eff}(Q) = H^2Q^2 + \frac{1}{2}g^2Q^4 - \frac{g\lambda}{3f}\dot{\phi}Q^3$$

$$J_* = -\frac{g\lambda}{f}Q_*^3$$



$$Q_* \approx \frac{\lambda}{2gf}\dot{\phi}$$

Condition:

$$\left|\frac{\lambda}{f}\dot{\phi}\right| > 4H$$

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; Mirzagholi, Maleknejad, Lozanov 2019]

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

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

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

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! → Ema's talk
- 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.