

# Removing the Cosmological Bound on the Axion Scale via Confinement During Inflation

In Collaboration with Gia Dvali and Lucy Komisel  
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# Strong $CP$ Problem and the Peccei-Quinn Solution

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- Non-trivial vacuum structure of QCD  
⇒ Topological  $\theta$ -term in the Lagrangian [Callan, Dashen, and Gross 1978]

$$\sim \theta \int \text{tr}(G_{\mu\nu} \tilde{G}^{\mu\nu}) \quad \tilde{G}^{\mu\nu} \equiv \epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}$$

- Measurable QCD vacuum angle induces nEDM [Baluni 1979]; [Crewther et al. 1979]  
with experimental bound [Baker et al. 2006]; [Pendlebury et al. 2015]; [Graner et al. 2016]

$$\bar{\theta} = \theta + \arg(\det M_Q) \lesssim 10^{-9}$$

⇒ Strong  $CP$ -Puzzle

# Strong $CP$ Problem and the Peccei-Quinn Solution

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- Peccei and Quinn (PQ) introduce spontaneously broken, anomalous and global symmetry  $U(1)_{PQ}$  [Peccei and Quinn 1977]

$$\Rightarrow \bar{\theta}_{eff} = \left( \frac{a}{f_a} - \bar{\theta} \right)$$

- Axion is degree of freedom relaxing  $\bar{\theta}_{eff} \sim 0$  and obtaining its potential only from  $\theta$ -term [Weinberg 1978]; [Wilczek 1978]  
 $\Rightarrow$  axion mass approximation

$$m_a^2 \sim \frac{\Lambda_C^4}{f_a^2}$$

# Removing the Cosmological Bound

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- Established cosmological upper bound on axion scale  $f_a \lesssim 10^{12} \text{GeV}$  [Preskill, Wise, and Wilczek 1983]; [Dine and Fischler 1983]; [Abbott and Sikivie 1983]
  - axion potential flat before QCD phase transition
  - initial misalignment angle  $\Delta\bar{\theta}_{in} \sim 1$ , i.e.  $a_0 \sim f_a$
- Strong coupling epoch during inflation [G. R. Dvali 1995]  
 $\Rightarrow$  initial oscillation amplitude reduces to  $a_0 \ll f_a$   
**IF**  $m_a$  dominates over Hubble parameter  $\mathcal{H}$

$$\ddot{a} + 3\mathcal{H}\dot{a} + \Lambda_C^4 \frac{\partial}{\partial a} \mathcal{V} \left( \frac{a}{f_a} - \bar{\theta} \right) = 0,$$

$$m_a \sim \frac{\Lambda_C^2}{f_a} \gtrsim \mathcal{H}$$

How do we increase the confinement scale?

# Removing the Cosmological Bound

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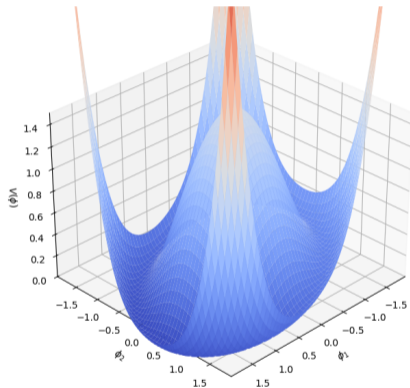


Figure: Tilted Hat potential after explicit symmetry breaking when instanton effects become relevant and lift the periodic potential for the axion.

# Minimal SU(5) Model

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- Minimal Georgi-Glashow SU(5) model [Georgi and Glashow 1974]
- 24 gauge bosons, 12 beyond the SM bosons (lepto-quark sector)
- Spontaneous symmetry breaking via two scalar Higgs fields

$$\Sigma \in \mathbf{24} \sim M_{\text{GUT}} \quad H \in \mathbf{5} \sim M_{\text{EW}}$$

- Fermions in anti-symmetric  $\mathbf{10}$  and anti-fundamental  $\bar{\mathbf{5}}$  representation

## Axion in SU(5) During Inflation

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- KSVZ [Kim 1979]; [Shifman, Vainshtein, and Zakharov 1980]: Add two Weyl fermions  $\Psi \in \mathbf{5}$ ,  $\bar{\Psi} \in \bar{\mathbf{5}}$  and scalar singlet  $\Phi$  transforming under  $U(1)_{PQ}$

$$\mathcal{L}_Y = g^u H \mathbf{10} \mathbf{10} + g^d H^\dagger \mathbf{10} \bar{\mathbf{5}} + g^F \Phi \bar{\Psi} \Psi + \text{h.c.}$$

$$\bar{\Psi} \rightarrow e^{i\frac{\alpha}{2}} \bar{\Psi} \qquad \Psi \rightarrow e^{i\frac{\alpha}{2}} \Psi \qquad \Phi \rightarrow e^{-i\alpha} \Phi$$

- DFSZ [Dine, Fischler, and Srednicki 1981]; [Zhitnitsky 1980]: Add second Higgs 5-plet and scalar singlet  $\Phi$  transforming under  $U(1)_{PQ}$

$$\mathcal{L}_Y = g^u H_u \mathbf{10} \mathbf{10} + g^d \bar{\mathbf{5}} \mathbf{10} H_d^\dagger + \text{h.c.}$$

$$\begin{aligned} H_u &\rightarrow e^{-i\alpha} H_u, & H_d &\rightarrow e^{i\alpha} H_d \\ \mathbf{10} &\rightarrow e^{i\frac{\alpha}{2}} \mathbf{10} & \bar{\mathbf{5}} &\rightarrow e^{i\frac{\alpha}{2}} \bar{\mathbf{5}} \end{aligned}$$

# Axion in SU(5) During Inflation

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- Inflation [Guth 1981] in SU(5) with inflaton  $S$  and PQ scalar  $\Phi$

$$V_S = (\kappa_\Sigma S^2 - M_\Sigma^2)\text{tr}\Sigma^2 + (\kappa_\Phi S^2 - M_\Phi^2)\Phi^\dagger\Phi + (\kappa_H S^2 - M_H^2)H^\dagger H,$$

$\Rightarrow$  Inflaton controls masses  $\Rightarrow$  controls confinement scale  $\Lambda_C$

- Confinement scale in **restored SU(5)  $\times$  U(1)<sub>PQ</sub>**:

$$\text{KSVZ : } \quad \Lambda_C \sim 2 \times 10^7 \text{ GeV}$$

$$\text{DFSZ : } \quad \Lambda_C \sim 5 \times 10^7 \text{ GeV}$$

# Confinement Scale in Restored SU(5)

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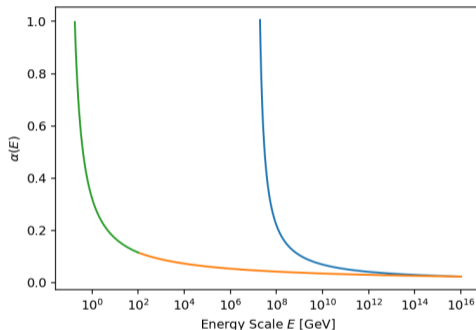


Figure: Running coupling of restored SU(5) in blue and of the QCD coupling in orange (six flavors running) and green(5 flavours running).

# Axion Mode Composition

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- Phase of PQ scalar  $\Phi = \rho_\Phi \exp(i\eta_\Phi/\rho_\Phi)$  and 't Hooft determinant  $\det\psi = \langle \det\psi \rangle \exp(i\eta_F/\rho_F)$ , with  $\langle \det\psi \rangle \propto \rho_F$ , compose the axion

$$a = \eta_F \cos(\xi) - \eta_\Phi \sin(\xi) \qquad \tan \xi \equiv \frac{\rho_\Phi}{\rho_F}$$

- Modulus of  $\det\psi$  comparable to confinement scale  $\rho_F \sim \Lambda_C$
- Today  $f_a \gg \Lambda_{\text{QCD}} \Rightarrow \eta_\Phi$  is predominantly the axion
- During inflation  $\rho_\Phi \approx 0 \Rightarrow \eta_F$  is the axion and  $f_a \sim \rho_F$ , s.t.

$$m_a \sim \Lambda_C$$

$\Rightarrow$  Axion sufficiently heavy to relax to the minimum during inflation!

$\Rightarrow$  Amplitude decreases as  $a_f = a_i e^{-\frac{3}{2}N_e}$ , where  $N_e = \mathcal{H}t$

# Summary






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- Inflaton restores  $SU(5) \times U(1)_{PQ} \Rightarrow$  controls masses and  $\Lambda_C$
- Higher confinement scale  $\Lambda_C \sim 10^7 \text{ GeV}$  in  $SU(5)$
- Axion composition changes with evolving universe
- During  $SU(5) \times U(1)_{PQ}$  inflation the axion is an  $\eta'$ -like particle
- Removes cosmological upper bound on  $f_a$  if  $\Lambda_C \sim m_a \gtrsim \mathcal{H}$

**Thank you for your attention!**






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## Confinement Scale in Restored SU(5)

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- 'Run' strong coupling in QCD vacuum bottom up to obtain starting point  $\alpha_S(M_{\text{GUT}}) \simeq 0.0224$
- 'Run' GUT coupling down until  $\alpha_{SU(5)} \sim 1$  with RG group equation

$$\Lambda_C \sim 10^{16} \text{GeV} \exp \left\{ -\frac{2\pi}{\beta_0} \left( \frac{1}{0.0224} - 1 \right) \right\}$$

- Insert  $\beta$ -function for different models

$$\text{DFSZ :} \quad \beta_0 = \frac{11}{3} \times 5 - \frac{2}{3} \left[ \frac{3}{2} + \frac{1}{2} \right] \times 3 = \frac{43}{3}$$

$$\text{KSVZ :} \quad \beta_0 = \frac{11}{3} \times 5 - \frac{2}{3} \left[ \frac{3}{2} + \frac{1}{2} \right] \times 3 - \frac{2}{3} \left[ \frac{1}{2} + \frac{1}{2} \right] = \frac{41}{3}$$

# The $\eta'$ as an Axion

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- $\eta'$  would-be Goldstone mode of  $U(1)_A$  spontaneously broken by chiral quark condensate  $\langle \bar{q}q \rangle$   
 $\Rightarrow$  phase of 't Hooft determinant contributes to  $\theta$ -term

$$\bar{\theta}_{eff} \supset \frac{\eta'}{f_{\eta'}}$$

- If Standard Model (SM) contains massless fermion  $\Rightarrow \eta'$  is the axion
- Massive fermions generate potential from Yukawa couplings  $\Rightarrow \eta'$  poor quality axion [G. Dvali, Komisel, and Wachowitz 2025]

## 't Hooft Determinant in KSVZ and DFSZ

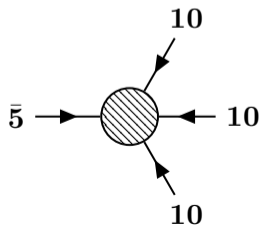
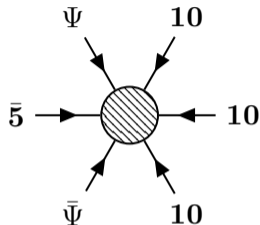
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- KSVZ-type model

$$\frac{1}{\Lambda^5} (\bar{\Psi}^r \Psi_r) (\mathbf{10}_{jk} \mathbf{10}_{mn} \mathbf{10}_{il} \bar{\mathbf{5}}^l \epsilon^{ijkmn}) + \dots$$

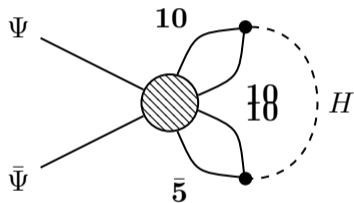
- DFSZ-type model

$$\frac{1}{\Lambda_C^2} (\mathbf{10}_{jk} \mathbf{10}_{mn} \mathbf{10}_{il} \bar{\mathbf{5}}^l) \epsilon^{ijkmn}$$



# 't Hooft Determinant in KSVZ and DFSZ

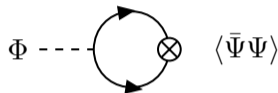
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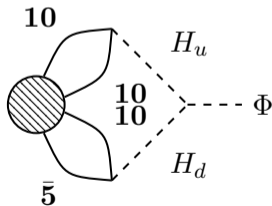
# Tadpole Diagrams

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- KSVZ tadpole from  $g^F \Phi \langle \bar{\Psi}^i \Psi_i \rangle$  inducing  $|\langle \Phi \rangle| \sim \Lambda_C^3 / M_{GUT}^2$



- DFSZ tadpole from  $\mu_\Phi H_u^\dagger H_d \Phi^\dagger$  inducing  $\langle \Phi \rangle \sim \frac{1}{M_{GUT}^2} \mu_\Phi g^u g^d \Lambda_C^2$



# Improvements and Alternatives

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- Introduce higher order operators to fix coupling unification and fermion masses

$$\propto H\mathbf{10}\Sigma\bar{\mathbf{5}} \quad \propto H\mathbf{10}\Sigma\mathbf{10} \quad (1)$$

- Introduce **45** to fix fermion masses
- Enlarge gauge group further to SO(10)
- Complex GUT Higgs acting as PQ field
- Complex inflaton acting as PQ field