Small size instanton effects in composite axion models

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DESY: Bright ideas for a dark universe 2021

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Introduction

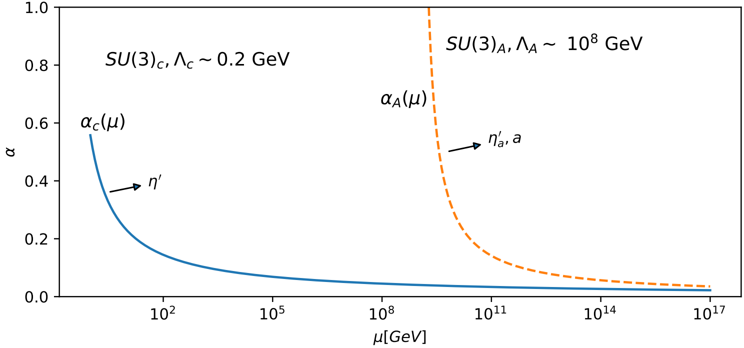
Strong CP-problem: Why is $\bar{\theta} \lesssim 10^{-10}$ so small?

- 1977 : Peccei-Quinn mechanism [9] introduce a dynamical solution that relaxes $\bar{\theta}$
- 1977/78 : Weinberg-Wilzcek axion [12, 13]
- 1979-81 : KSVZ [7], DFSZ [4]
- 1985 : dynamical axion[3]: axion results as a composite state

- 2018 : Agrawal, Howe : non-trivial embedding of QCD leads to extra contributions from UV-instantons[1]
- 2018-20 : New (high quality) axion models with large mass, i.e. Gaillard et al. : $SU(6)$ Color unification [5]

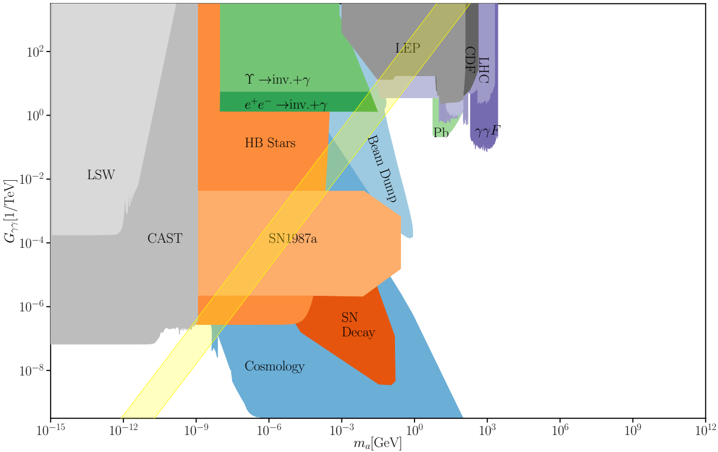
Introduction

axion quality problem: sensitivity to anomalous symmetry breakings at *all* scales



How do (small size) UV-instantons influence phenomenology of an axion/η'?

Introduction



$$g_{a\gamma\gamma} \sim \alpha/f_a, \quad m_a^2 f_a^2 \sim \Lambda^4 \qquad [2]$$

Instanton contributions

- $U(1)$-problem and large η' mass: solved by additional determinantal term due to instanton background [10]

$\rightarrow$ determinantal terms are included into pseudoscalar potential to achieve a correct mass matrix [8]

- usually axion is rotated into quark mass matrix for matching

$\mathrm{Tr}(\Sigma M)$

$e^{i\gamma_5\alpha}$

$\mathrm{Det}(\Sigma M)$

Instead we treat the axion as a phase of the *determinantal term* to derive the correct mixing behaviour and correct instanton sensitivity of the axion

Recent Models

Focusing on Gaillard et al. Color Unification model [5], we derive the following axion potential:

$$
\begin{aligned}
-V =& m_u v^3 \cos\left(\frac{\pi^0}{F_{\pi^0}} + \frac{\eta'}{F_{\eta'}}\right) + m_d v^3 \cos\left(-\frac{\pi^0}{F_{\pi^0}} + \frac{\eta'}{F_{\eta'}}\right) \\
&+ \frac{v_{\text{diag}}^3 v^9}{K^8} \cos\left(2\frac{\phi_2}{F_a} + 2\frac{\eta'}{F_{\eta'}}\right) \\
&+ \frac{v_{\text{diag}}^3 v^6 m_u \Lambda_u^2}{K^8} \cos\left(2\frac{\phi_2}{F_a} + \frac{\eta'}{F_{\eta'}}\right) \\
&+ \frac{v_{\text{diag}}^3 v^6 m_d \Lambda_d^2}{K^8} \cos\left(2\frac{\phi_2}{F_a} + \frac{\eta'}{F_{\eta'}} - \frac{\pi^0}{F_{\pi^0}}\right) \\
&+ K' v_{\text{diag}}^3 \cos\left(2\frac{\phi_2}{F_a}\right) + K_{\text{diag}} v_{\text{diag}}^3 \cos\left(2\frac{\phi_2}{F_a} + \sqrt{6}\frac{\phi_1}{F_a}\right).
\end{aligned}
$$

Recent Models

The corresponding mass matrix is

$$M = \begin{pmatrix} \frac{4}{F_a^2}(\Lambda_{\rm SSI}^4 + \Lambda_{\rm diag}^4) & \frac{1}{F_a^2} 2\sqrt{6}\Lambda_{\rm diag}^4 & 0 & 0 \\ \frac{1}{F_a^2} 2\sqrt{6}\Lambda_{\rm diag}^4 & \frac{6}{F_a^2}(\Lambda_{\rm diag}^4 + 4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\rm inst}^3) & \frac{2}{F_a F_{\eta'}}(4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\rm inst}^3) & 0 \\ 0 & \frac{2}{F_a F_{\eta'}}(4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\rm inst}^3) & \frac{1}{F_{\eta'}^2}(m_+ v^3 + 4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\rm inst}^3) & \frac{-1}{F_{\pi^0} F_{\eta'}} m_- v^3 \\ 0 & 0 & \frac{-1}{F_{\pi^0} F_{\eta'}} m_- v^3 & \frac{1}{F_{\pi^0}^2}(m_+ v^3 + 2\mu\Lambda_{\rm inst}^3) \end{pmatrix}.$$

New scaling relations:

$$m_a^2 F_a^2 = 6(m_{a,0}^2 F_a^2 + \Lambda_d^4) - \frac{6\Lambda_d^8}{\Lambda_{\mathrm{SSI}}^4} + \mathcal{O}\left(\frac{1}{\Lambda_{\mathrm{SSI}}^5}\right)$$

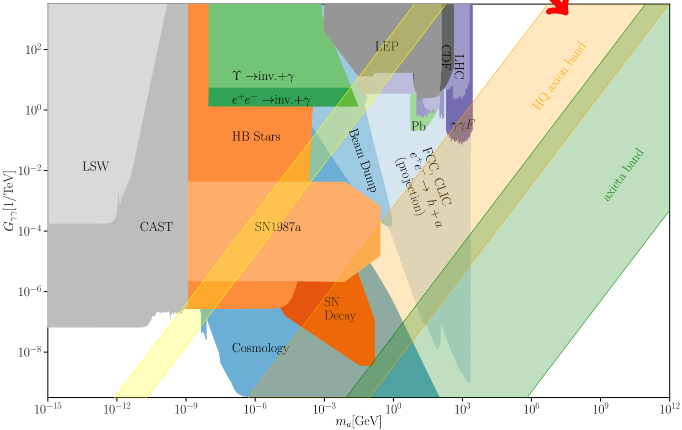
$$m_{\eta_a'}^2 F_{\eta_a'}^2 = 4(\Lambda_{\mathrm{SSI}}^4 + \Lambda_d^4) + \mathcal{O}\left(\frac{1}{\Lambda_{\mathrm{SSI}}^5}\right)$$

New e.m. coupling depending on the axion eigenvector v_a:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi F_a}\left(\frac{E}{N} - c_\chi'(v_a)\right), \qquad c_\chi' > c_\chi = 1.92(4)$$

Recent models: results

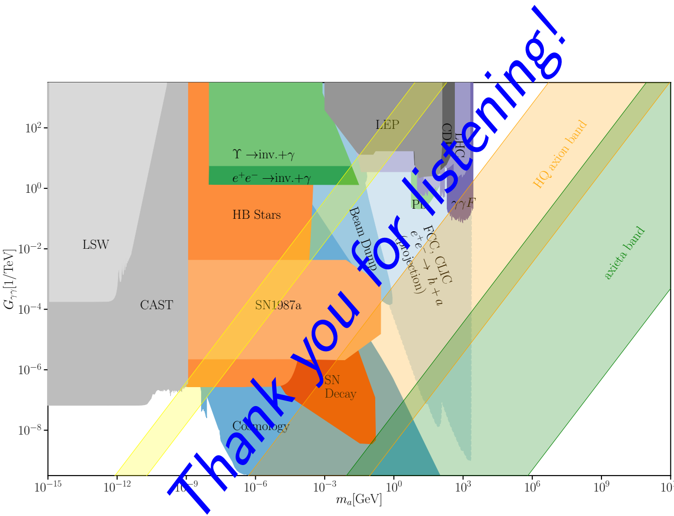
new axion band predicts *high mass* and is *broader* due to possible instanton effects



[2]

$\Lambda_d = 10$ TeV, $\Lambda_{SSI} = 0.1$ to 100 TeV

Recent models: results



[2]

$\Lambda_d = 10$ TeV, $\Lambda_{SSI} = 0.1$ to 100 TeV

Backup:Vanilla QCD-axion

The results are to first order in the limit $F_a \gg 0$, $m_u \approx m_d$

$$m_{\pi^0}^2 = \frac{m_+ v^3 + 2\mu\Lambda_{\text{inst}}^3}{F_{\pi^0}^2},$$

$$m_{\eta'}^2 = \frac{m_+ v^3 + 4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\text{inst}}^3}{F_{\eta'}^2},$$

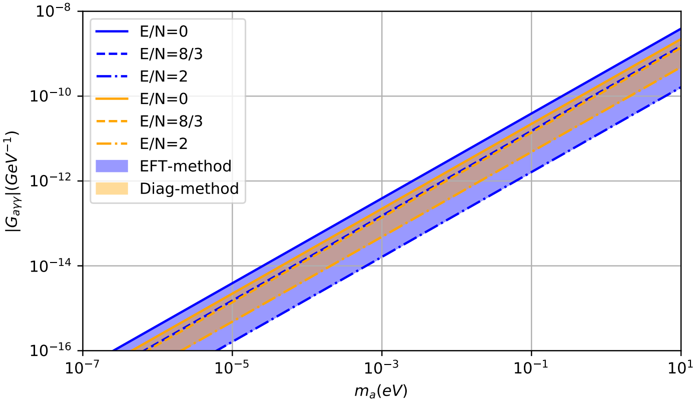
$$m_a^2 F_a^2 = \begin{cases} \frac{m_{\pi^0}^2 F_{\pi^0}^2}{4}\left(1 - \frac{m_{\pi^0}^2 F_{\pi^0}^2}{m_{\eta'}^2 F_{\eta'}^2}\right) + \cdots & , m_q \to 0 \\ \frac{Z}{(1+Z)^2} m_{\pi^0}^2 F_{\pi^0}^2 + \cdots & , \Lambda_{\eta'} \to \infty \end{cases}$$

$$m_a \approx 0.866(5)\text{eV}\left(\frac{10^7\text{GeV}}{F_a}\right)$$

Backup:Vanilla QCD-axion

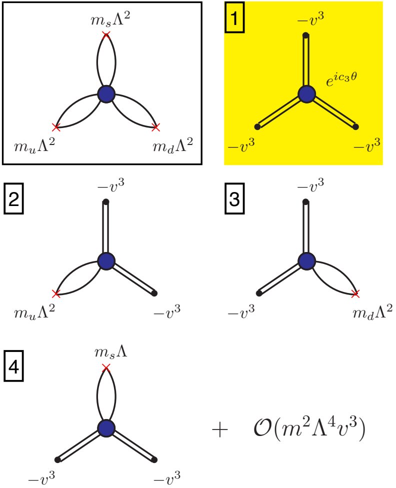
$$G_{A\gamma\gamma} = \frac{\alpha}{2\pi F_a}\left(\frac{E}{N} - c_\chi\right),$$

$c_\chi = 1.57(7)$, EFT-framework [11]:$c_\chi = 1.92(4)$



Backup:instanton diagrams usual axion

from [8, 6]



Backup: Cross Check

resulting mass matrix: [8, 6])

$$\begin{pmatrix} \frac{1}{F_a^2}(\Lambda_{\eta'}^4 + 2\mu\Lambda_{\text{inst}}^3) & \frac{-2}{F_a F_{\eta'}}(\Lambda_{\eta'}^4 + \mu\Lambda_{\text{inst}}^3) & 0 \\ \frac{-2}{F_a F_{\eta'}}(\Lambda_{\eta'}^4 + \mu\Lambda_{\text{inst}}^3) & \frac{1}{F_{\eta'}^2}(m_+ v^3 + 4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\text{inst}}^3) & \frac{-1}{F_{\pi^0} F_{\eta'}} m_- v^3 \\ 0 & \frac{-1}{F_{\pi^0} F_{\eta'}} m_- v^3 & \frac{1}{F_{\pi^0}^2}(m_+ v^3 + 2\mu\Lambda_{\text{inst}}^3) \end{pmatrix}$$

$$m_+ = (m_u + m_d), \qquad m_- = (m_d - m_u), \qquad \Lambda_{\eta'}^4 = \frac{v^9}{K^5},$$

$$\Lambda_{\text{inst}}^3 = \frac{L^2}{K^2} v^3, \qquad m_u \Lambda_u^2 + m_d \Lambda_d^2 = \mu L^2$$

Backup:Gaillard models

from [5]

	$SU(6)$	$SU(3')$
Q_L	$\square$	1
U_L^c	$\bar{\square}$	1
D_L^c	$\bar{\square}$	1
Ψ_L	20	1
q_L'	1	$\bar{\square}$
$u_L'^c$	1	$\square$
$d_L'^c$	1	$\square$
Δ	$\square$	$\bar{\square}$

	$SU(3)_c$	$SU(3)_{\text{diag}}$	$SU(2)_L$	$U(1)_Y$
q_L	$\square$	1	$\square$	$\frac{1}{6}$
$\mathbf{\tilde{q}_L}$	1	$\square$	$\square$	$\frac{1}{6}$
u_L^c	$\bar{\square}$	1	1	$-\frac{2}{3}$
$\mathbf{\tilde{u}_L^c}$	1	$\bar{\square}$	1	$-\frac{2}{3}$
d_L^c	$\bar{\square}$	1	1	$\frac{1}{3}$
$\mathbf{\tilde{d}_L^c}$	1	$\bar{\square}$	1	$\frac{1}{3}$
ψ_L	$\square$	$\bar{\square}$	1	0
ψ_L^c	$\bar{\square}$	$\square$	1	0
$2 \times \psi_\nu$	1	1	1	1
$\mathbf{q_L'}$	1	$\bar{\square}$	$\square$	$-\frac{1}{6}$
$\mathbf{u_L'^c}$	1	$\square$	1	$\frac{2}{3}$
$\mathbf{d_L'^c}$	1	$\square$	1	$-\frac{1}{3}$
–	–	–	1	0

Backup:Gaillard models

from [5]

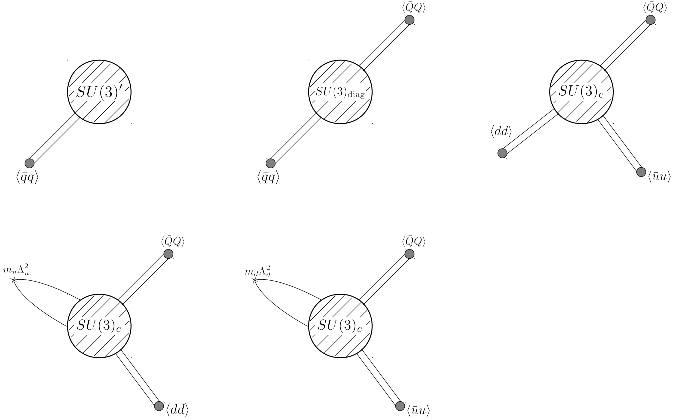
model 1:

	$SU(3)_{\text{diag}}$	$SU(3)_c$	$SU(3)'$
Q	$\square$	$\square$	-
q	$\square$	1	$\square$

model 2:

	$SU(3)_{\text{diag}}$	$SU(3)_c$	$SU(3)'$	$SU(6)$
Q	$\square$	$\square$	-	-
Δ_2	-	-	$\overline{\square}$	$\square$

Backup:Gaillard models



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