Implication of High Quality QCD axion in Dual Description

Choi, Leedom[2306.XXXXX]
Burgess, Choi, Quevedo [2301.00549]

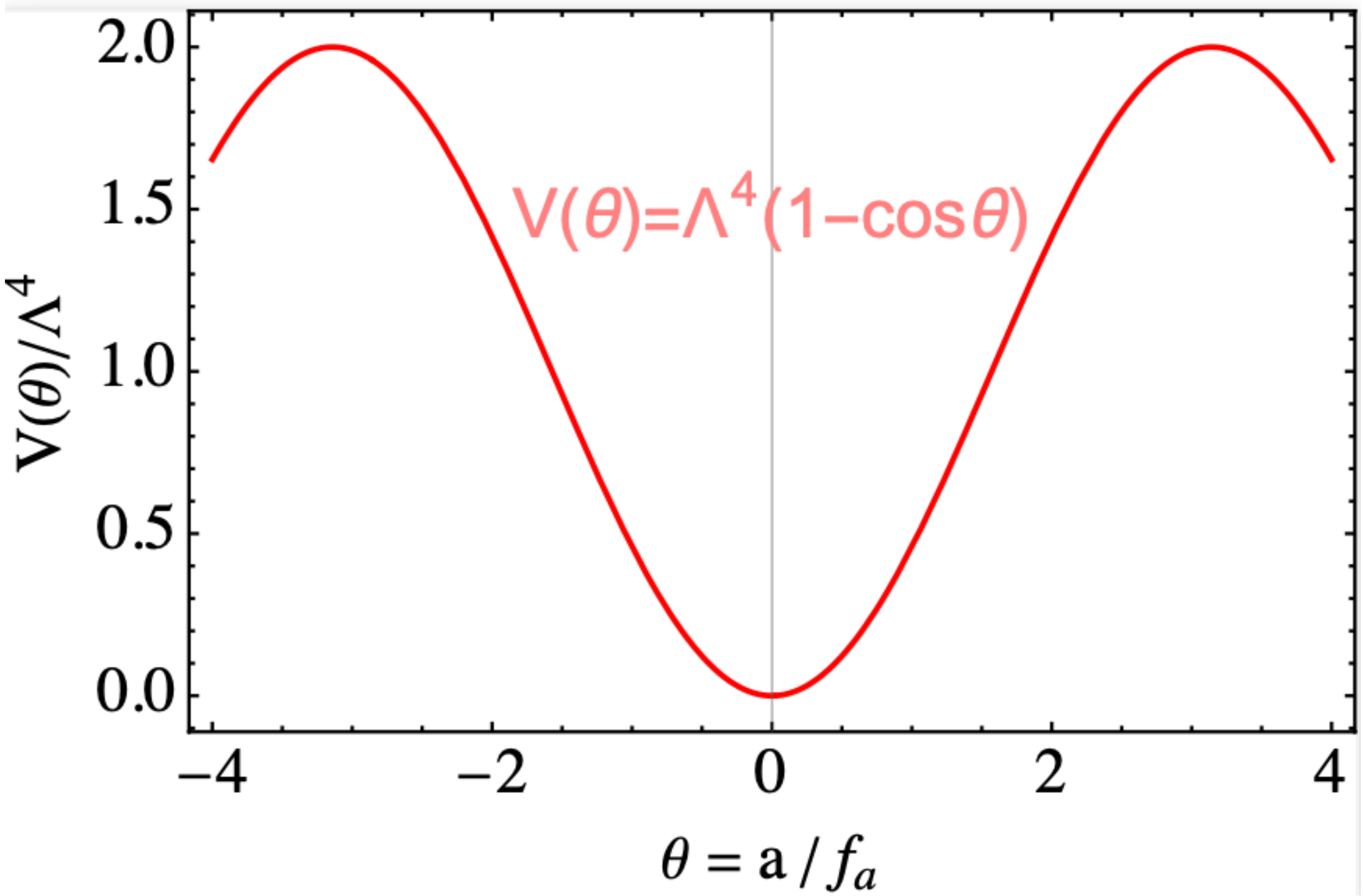
Gongjun Choi (CERN)

NPKI 2023
6/6/2023

Outline

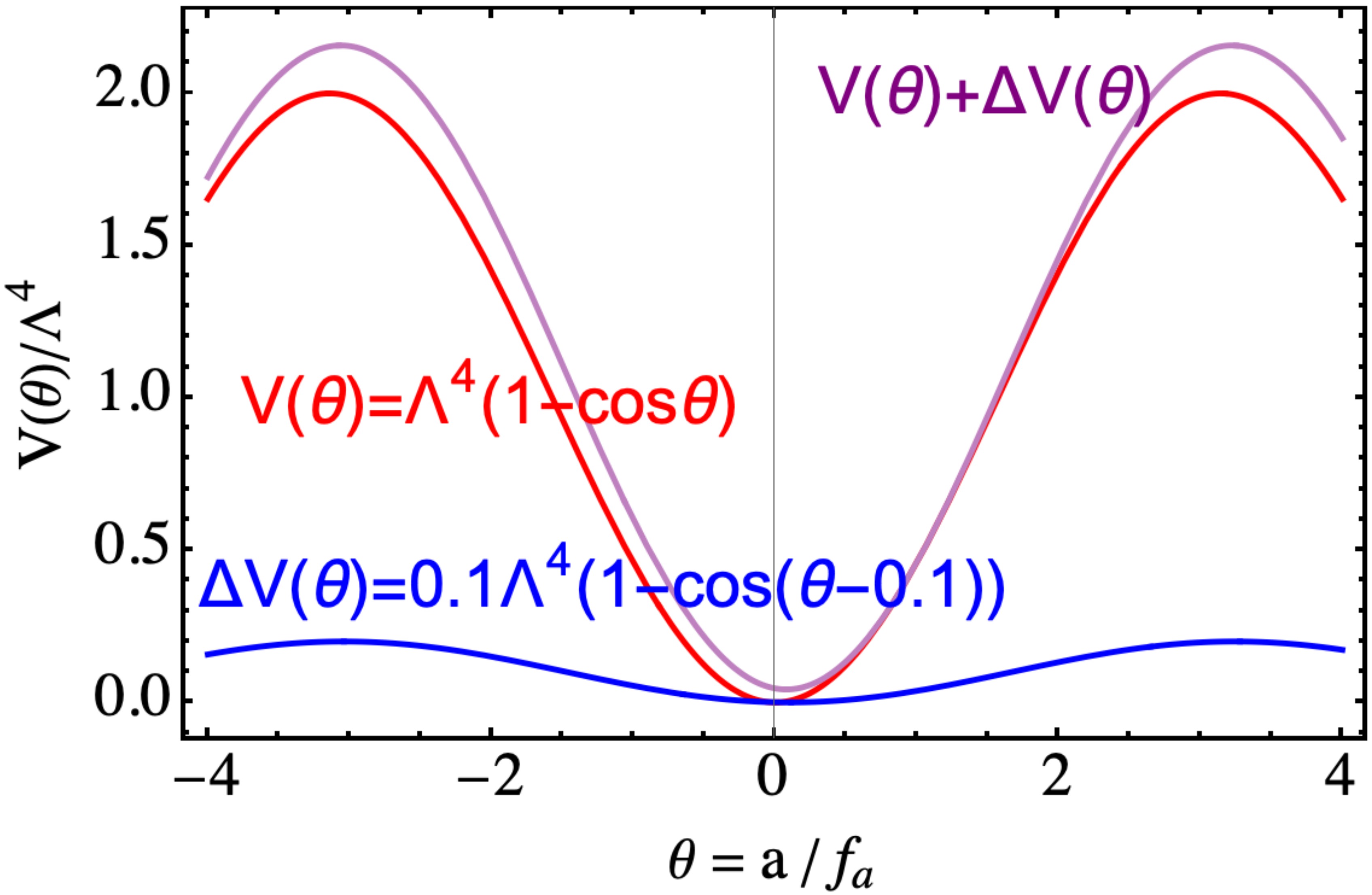
- Axion Quality Problem (in PQ picture)
- QCD axion in dual description
- QCD Axion Quality in dual description
- Implication of High Quality QCD axion in dual description

QCD axion quality problem in PQ picture



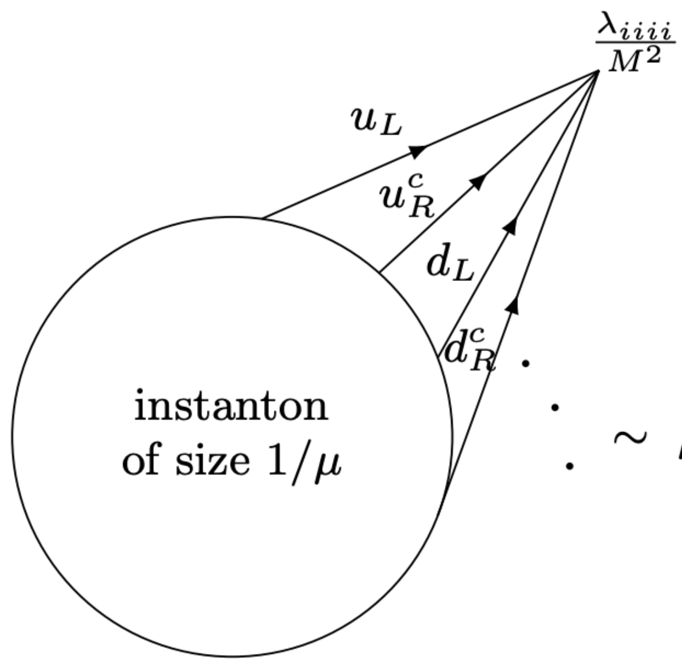
Good sol to strong CP problem iff $\theta_{min} < 10^{-10}$

QCD axion quality problem in PQ picture



If $\theta_{min} \sim \Delta V / V > 10^{-10}$, no more meaning in axion

- Coefficient of an operator closing fermion zero modes is generally complex



$$\sim \mu^4 \prod_{i=1}^{3} \frac{\mu^2 \lambda_{iiii}}{M^2} e^{-\frac{8\pi}{g^2(\mu)} - i\theta}$$

- Coefficient of a global symmetry breaking non-renormalizable operator is complex

Kamionkowski, March-Russell 92
Barr, Seckel 92

$$c \frac{\Phi^5}{M_P} + c^* \frac{\Phi^{\dagger\, 5}}{M_P}$$

Dual formulation of QCD axion

- Below Λ_{QCD}, there is a counterpart of CS 3-form, $C_{\mu\nu\lambda}$

$$\mathcal{L}(C) \supset -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda_{\rm QCD}^2 H_{\mu\nu\lambda\rho}$$

where $\Lambda_{QCD}^2 H = \Lambda_{QCD}^2 dC = F \wedge F$.

- Charge density

$$q(x) \equiv (1/16\pi^2)\mathrm{Tr}[F_{\mu\nu}\tilde{F}^{\mu\nu}] \qquad \langle q(x)\rangle \propto \sin\theta$$

- θ characterizes a phase of 3-form gauge theory

$$\int d^4x \langle q(x)q(0)\rangle = \frac{1}{i}\frac{\partial}{\partial\theta}\langle q(0)\rangle \begin{cases} = 0, & \text{for massive } C \\ \neq 0, & \text{for massless } C \end{cases}$$

Dvali 05

Lüscher 78

Dual formulation of QCD axion

- Below Λ_{QCD}, there is a counterpart of CS 3-form, $C_{\mu\nu\lambda}$

$$\mathcal{L}(C) \supset -\frac{1}{2\cdot 4!} H_{\mu\nu\lambda\rho} H^{\mu\nu\lambda\rho} - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda_{\rm QCD}^2 H_{\mu\nu\lambda\rho}$$

where $\Lambda_{QCD}{}^2 H = \Lambda_{QCD}{}^2 dC = F \wedge F$.

∃ long-range Coulomb-type force

- Charge density

$$q(x) \equiv (1/16\pi^2)\mathrm{Tr}[F_{\mu\nu}\tilde{F}^{\mu\nu}] \qquad \langle q(x)\rangle \propto \sin\theta$$

- θ characterizes a phase of 3-form gauge theory

$$\int d^4x \langle q(x) q(0)\rangle = \frac{1}{i}\frac{\partial}{\partial\theta}\langle q(0)\rangle \begin{cases} = 0, & \text{for massive } C \\ \neq 0, & \text{for massless } C \end{cases}$$

Dvali 05

Lüscher 78

Dual formulation of QCD axion

- Below Λ_{QCD}, there is a counterpart of CS 3-form, $C_{\mu\nu\lambda}$

$$\mathcal{L}(C) \supset -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda^2_{\rm QCD}H_{\mu\nu\lambda\rho}$$

where $\Lambda_{QCD}{}^2 H = \Lambda_{QCD}{}^2 dC = F \wedge F$.

∃ long-range Coulomb-type force

- Charge density

$$q(x) \equiv (1/16\pi^2)\mathrm{Tr}[F_{\mu\nu}\tilde{F}^{\mu\nu}] \qquad \langle q(x)\rangle \propto \sin\theta$$

- θ characterizes a phase of 3-form gauge theory

$$\int d^4x\langle q(x)q(0)\rangle = \frac{1}{i}\frac{\partial}{\partial\theta}\langle q(0)\rangle \begin{cases} = 0, & \text{for massive } C \\ \neq 0, & \text{for massless } C \end{cases}$$

$q(x) \sim dC \neq 0$

Dvali 05

Lüscher 78

Dual formulation of QCD axion

- Below Λ_{QCD}, there is a counterpart of CS 3-form, $C_{\mu\nu\lambda}$

$$\mathcal{L}(C) \supset -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda^2_{\rm QCD}H_{\mu\nu\lambda\rho}$$

where $\Lambda_{QCD}^2 H = \Lambda_{QCD}^2 dC = F \wedge F$.

Massive C → θ=0!

- Charge density

$$q(x) \equiv (1/16\pi^2)\mathrm{Tr}[F_{\mu\nu}\tilde{F}^{\mu\nu}] \qquad \langle q(x)\rangle \propto \sin\theta$$

- θ characterizes a phase of 3-form gauge theory

$$\int d^4x\langle q(x)q(0)\rangle \;=\; \frac{1}{i}\frac{\partial}{\partial\theta}\langle q(0)\rangle \begin{cases} = 0, & \text{for massive } C \\ \neq 0, & \text{for massless } C \end{cases}$$

Dvali 05

Lüscher 78

Dual formulation of QCD axion

- θ=0 corresponds to Higgs phase of 3-form gauge theory
  → strong CP problem is translated to how to make CS 3-form massive

- Introduce 2-form field $B_{\mu\nu}$ giving the gauge invariant mass term $\propto (dB - mC)^2$

Dvali 05

- 2-form enjoys the gauged shift symmetry

$$B_{\mu\nu} \to B_{\mu\nu} + \Omega_{\mu\nu} \qquad \Omega_{\mu\nu} = A^a_{[\mu}\partial_{\nu]}\omega^a$$

- Dualizing 2-form gives the axion theory.

Dual formulation of QCD axion

- After introducing 2-form

$$
\begin{aligned}
\mathcal{L}(C,B) \supset & -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{2\cdot 3!}G_{\mu\nu\lambda}G^{\mu\nu\lambda} \\
& -\frac{1}{3!}\,\frac{\epsilon^{\mu\nu\lambda\rho}}{f_a}G_{\mu\nu\lambda}J_\rho - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda^2_{\rm QCD}H_{\mu\nu\lambda\rho} \\
& -\frac{a}{3!}\,\epsilon^{\mu\nu\lambda\rho}\left(\partial_\mu G_{\nu\lambda\rho} - \frac{1}{4}\frac{\Lambda^2_{\rm QCD}}{f_a}\,H_{\mu\nu\lambda\rho}\right)
\end{aligned}
$$

where H = dC, G = dB + m_aC.

Dual formulation of QCD axion

- After introducing 2-form

$$\mathcal{L}(C,B) \supset -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{2\cdot 3!}G_{\mu\nu\lambda}G^{\mu\nu\lambda}$$
$$-\frac{1}{3!}\frac{\epsilon^{\mu\nu\lambda\rho}}{f_a}G_{\mu\nu\lambda}J_\rho - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\mathrm{QCD}}\Lambda^2_{\mathrm{QCD}}H_{\mu\nu\lambda\rho}$$
$$-\frac{a}{3!}\epsilon^{\mu\nu\lambda\rho}\left(\partial_\mu G_{\nu\lambda\rho} - \frac{1}{4}\frac{\Lambda^2_{\mathrm{QCD}}}{f_a}H_{\mu\nu\lambda\rho}\right)$$

where H = dC, G = dB + m_aC.

Mixing of B and C

Dual formulation of QCD axion

- After introducing 2-form

$$\mathcal{L}(C,B) \supset -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{2\cdot 3!}G_{\mu\nu\lambda}G^{\mu\nu\lambda}$$
$$-\frac{1}{3!}\frac{\epsilon^{\mu\nu\lambda\rho}}{f_a}G_{\mu\nu\lambda}J_\rho - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda^2_{\rm QCD}H_{\mu\nu\lambda\rho}$$
$$-\frac{a}{3!}\epsilon^{\mu\nu\lambda\rho}\left(\partial_\mu G_{\nu\lambda\rho} - \frac{1}{4}\frac{\Lambda^2_{\rm QCD}}{f_a}H_{\mu\nu\lambda\rho}\right)$$

where H = dC, G = dB + m_aC.

- Impose Bianchi identity dG - (Λ^2/f)X = 0

$$X \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho}H_{\mu\nu\lambda\rho}$$

Dual formulation of QCD axion

- After introducing 2-form

$$\mathcal{L}(C,B) \supset -\frac{1}{2\cdot 4!}H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} - \frac{1}{2\cdot 3!}G_{\mu\nu\lambda}G^{\mu\nu\lambda}$$
$$-\frac{1}{3!}\frac{\epsilon^{\mu\nu\lambda\rho}}{f_a}G_{\mu\nu\lambda}J_\rho - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\theta_{\rm QCD}\Lambda_{\rm QCD}^2 H_{\mu\nu\lambda\rho}$$
$$-\frac{a}{3!}\epsilon^{\mu\nu\lambda\rho}\left(\partial_\mu G_{\nu\lambda\rho} - \frac{1}{4}\frac{\Lambda_{\rm QCD}^2}{f_a}H_{\mu\nu\lambda\rho}\right)$$

where H = dC, G = dB + m_aC.

- Impose Bianchi identity dG - (Λ^2/f)X = 0

- "a" is a Lagrange multiplier
→ will be identified with the axion later.

Dual formulation of QCD axion

- Integrate out G (B) gives

$$\mathcal{L}(C, \quad, a) = -\frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{f_a} J^\mu \partial_\mu a - \frac{1}{2f_a^2} J_\mu J^\mu$$
$$+ (m_a a - \theta_{\rm QCD}\Lambda_{\rm QCD}^2)X$$
$$- \frac{1}{2}X^2$$

- From e.o.m of axion

$$\frac{\partial V(a)}{\partial a} = m_a X \qquad\qquad X \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho} H_{\mu\nu\lambda\rho}$$

- Vanishing X corresponds to extrema of V(a)
  → dynamically driven to minimum of V(a)
  → X ~ θ = 0

QCD axion quality in dual description

- Another 3-form $E_{\mu\nu\lambda}$ coupled to axion

$$\mathcal{L}(C,E,B) \supset -\frac{1}{2\cdot 4!}\Big(H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} + K_{\mu\nu\lambda\rho}K^{\mu\nu\lambda\rho}\Big) - \frac{1}{2\cdot 3!}G_{\mu\nu\lambda}G^{\mu\nu\lambda} - \frac{1}{3!}\frac{\epsilon^{\mu\nu\lambda\rho}}{f_a}G_{\mu\nu\lambda}J_\rho - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\left(\theta_{\rm QCD}\Lambda_{\rm QCD}^2 H_{\mu\nu\lambda\rho} + \theta_h\Lambda_h^2 K_{\mu\nu\lambda\rho}\right)$$

where H = dC, K = dE, G = dB + m_aC + M_aE.

- Dualizing the theory gives

$$\frac{\partial V(a)}{\partial a} = m_a X + M_a Y$$

$$X \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho}H_{\mu\nu\lambda\rho}$$

$$Y \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho}K_{\mu\nu\lambda\rho}$$

QCD axion quality in dual description

- Another 3-form $E_{\mu\nu\lambda}$ coupled to axion

$$\mathcal{L}(C,E,B) \supset -\frac{1}{2\cdot 4!}\left(H_{\mu\nu\lambda\rho}H^{\mu\nu\lambda\rho} + K_{\mu\nu\lambda\rho}K^{\mu\nu\lambda\rho}\right) - \frac{1}{2\cdot 3!}G_{\mu\nu\lambda}G^{\mu\nu\lambda} - \frac{1}{3!}\frac{\epsilon^{\mu\nu\lambda\rho}}{f_a}G_{\mu\nu\lambda}J_\rho - \frac{1}{4!}\epsilon^{\mu\nu\lambda\rho}\left(\theta_{\rm QCD}\Lambda_{\rm QCD}^2 H_{\mu\nu\lambda\rho} + \theta_h\Lambda_h^2 K_{\mu\nu\lambda\rho}\right)$$

where $H = dC$, $K = dE$, $G = dB + m_a C + M_a E$.

- Dualizing the theory gives

$$\frac{\partial V(a)}{\partial a} = m_a X + M_a Y$$

$$X \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho}H_{\mu\nu\lambda\rho}$$

$$Y \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho}K_{\mu\nu\lambda\rho}$$

a_{min} does not correspond to $\theta\sim X=0$!

QCD axion quality in dual description

- From e.o.m of C and E

$$X = m_a\, a - \theta_{\rm QCD}\Lambda_{\rm QCD}^2, \quad Y = M_a\, a - \theta_h \Lambda_h^2$$

- Global min of V(a)

$$a_{\rm min,X} = \frac{\theta_{\rm QCD}\Lambda_{\rm QCD}^2}{m_a} \qquad a_{\rm min,X,Y} = \frac{m_a\theta_{\rm QCD}\Lambda_{\rm QCD}^2 + M_a\theta_h\Lambda_h^2}{m_a^2 + M_a^2}$$

- Shift in a_{min}

$$\Delta\theta_{\rm min} = \frac{a_{\rm min,X,Y} - a_{\rm min,X}}{f_a} = \begin{cases} \theta_h \frac{M_a}{m_a}\left(\frac{\Lambda_h}{\Lambda_{\rm QCD}}\right)^2, & \text{for } m_a > M_a \\ \theta_h - \theta_{\rm QCD}, & \text{for } m_a < M_a \end{cases}$$

Higgsing all the 3-forms

- How to switch-off contribution to V(a) from other 3-forms than QCD one?
  →# of 2-forms = # of 3-forms

- Consider second 2-form $\tilde{B}$ with $\tilde{G} = d\tilde{B} + M_b E$ and Bianchi identity

$$-\frac{b}{3!}\,\epsilon^{\mu\nu\lambda\rho}\left(\partial_\mu \tilde{G}_{\nu\lambda\rho} - \frac{1}{4}\frac{\Lambda_h^2}{f_b}\,K_{\mu\nu\lambda\rho}\right)$$

- Integrating out G,C and E gives

$$\frac{\partial V(a)}{\partial a} = m_a X + M_a Y \qquad \frac{\partial V(b)}{\partial b} = M_b Y$$

Higgsing all the 3-forms

- Move to new basis

$$\bar{m}_a \bar{X} = m_a X + M_a Y, \quad \bar{m}_b \bar{Y} = M_b Y$$

  which gives

$$\frac{\partial V(a)}{\partial a} = \bar{m}_a \bar{X} \quad , \quad \frac{\partial V(b)}{\partial b} = \bar{m}_b \bar{Y}$$

- The correspondence btw vanishing 4-form electric field (~θ) and a_{min} is restored!

- Can be readily generalized to multiple 3-form cases.

- # of 2-forms = # of 3-forms guarantees θ ~ X = 0

Higgsing all the 3-forms

- Move to new basis

$$\bar{m}_a \bar{X} = m_a X + M_a Y, \quad \bar{m}_b \bar{Y} = M_b Y$$

which gives

$$\frac{\partial V(a)}{\partial a} = \bar{m}_a \bar{X} \quad , \quad \frac{\partial V(b)}{\partial b} = \bar{m}_b \bar{Y}$$

- The correspondence btw vanishing 4-form electric field (~θ) and a_{min} is restored!

- Can be readily generalized to multiple 3-form cases.

Multiple axions enhancing the quality of QCD axion!

- # of 2-forms = # of 3-forms guarantees θ ~ X = 0

Implication: QCD axion, sub-eV ALP

- Consider (1) QCD axion couples to C and E
  (2) b-axion couples to E only

- After integrating out two 2-forms,

$$\mathcal{L}(X,Y) \supset -\frac{1}{2}X^2 - \frac{1}{2}Y^2 + a m_a X + (aM_a + bM_b)Y$$

which gives (after integrating out X,Y)

$$V(a,b) = \frac{1}{2}m_a^2 a^2 + \frac{1}{2}(M_a a + M_b b)^2 \qquad M_a = \frac{\Lambda_h^2}{f_a} \qquad M_b = \frac{\Lambda_h^2}{f_b}$$

- In the mass eigenbasis ($r = M_b/M_a = f_a/f_b$)

$$\begin{aligned} a &= -\frac{r}{\sqrt{1+r^2}}a' + \frac{1}{\sqrt{1+r^2}}b', \\ b &= \frac{1}{\sqrt{1+r^2}}a' + \frac{r}{\sqrt{1+r^2}}b'. \end{aligned} \qquad (m_{a'})^2 \simeq \left(\frac{r}{\sqrt{1+r^2}}\right)^2 m_a^2, \quad (m_{b'})^2 \simeq (1+r^{-2})M_b^2$$

Implication: QCD axion, sub-eV ALP

- From QCD axion-U(1)$_{em}$ coupling

$$\mathcal{L} \supset \left(\frac{r}{\sqrt{1+r^2}} a' - \frac{1}{\sqrt{1+r^2}} b' \right) \frac{g}{8} \epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$$

- Define

$$g_{a\gamma\gamma} \equiv -\frac{gr}{\sqrt{1+r^2}}, \quad g_{b\gamma\gamma} \equiv \frac{g}{\sqrt{1+r^2}}$$

Implication: QCD axion, sub-eV ALP

- From QCD axion-$U(1)_{em}$ coupling

$$\mathcal{L} \supset \left(\frac{r}{\sqrt{1+r^2}}a' - \frac{1}{\sqrt{1+r^2}}b'\right)\frac{g}{8}\epsilon^{\mu\nu\rho\lambda}F_{\mu\nu}F_{\rho\lambda}$$

- Define

$$g_{a\gamma\gamma} \equiv -\frac{gr}{\sqrt{1+r^2}}, \quad g_{b\gamma\gamma} \equiv \frac{g}{\sqrt{1+r^2}}$$

Identified with the known QCD axion-photon coupling

$g_{a\gamma\gamma} \sim \alpha_{em}/(2\pi F_a)$

Implication: QCD axion, sub-eV ALP

- From QCD axion-$U(1)_{em}$ coupling

$$\mathcal{L} \supset \left(\frac{r}{\sqrt{1+r^2}} a' - \frac{1}{\sqrt{1+r^2}} b' \right) \frac{g}{8} \epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$$

- Define

$$g_{a\gamma\gamma} \equiv -\frac{gr}{\sqrt{1+r^2}}, \quad g_{b\gamma\gamma} \equiv \frac{g}{\sqrt{1+r^2}}$$

Induced coupling of b-axion to photon

Implication: QCD axion, sub-eV ALP

- From QCD axion-$U(1)_{em}$ coupling

$$\mathcal{L} \supset \left(\frac{r}{\sqrt{1+r^2}} a' - \frac{1}{\sqrt{1+r^2}} b' \right) \frac{g}{8} \epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$$

- Define

$$g_{a\gamma\gamma} \equiv -\frac{gr}{\sqrt{1+r^2}}, \quad g_{b\gamma\gamma} \equiv \frac{g}{\sqrt{1+r^2}}$$

For $r \ll 1$, $g_{b\gamma\gamma} \gg g_{a\gamma\gamma}$

Implication: QCD axion, sub-eV ALP

- For $r \ll 1$, $r = f_a/f_b = f_a/F_a$
- Mass and coupling

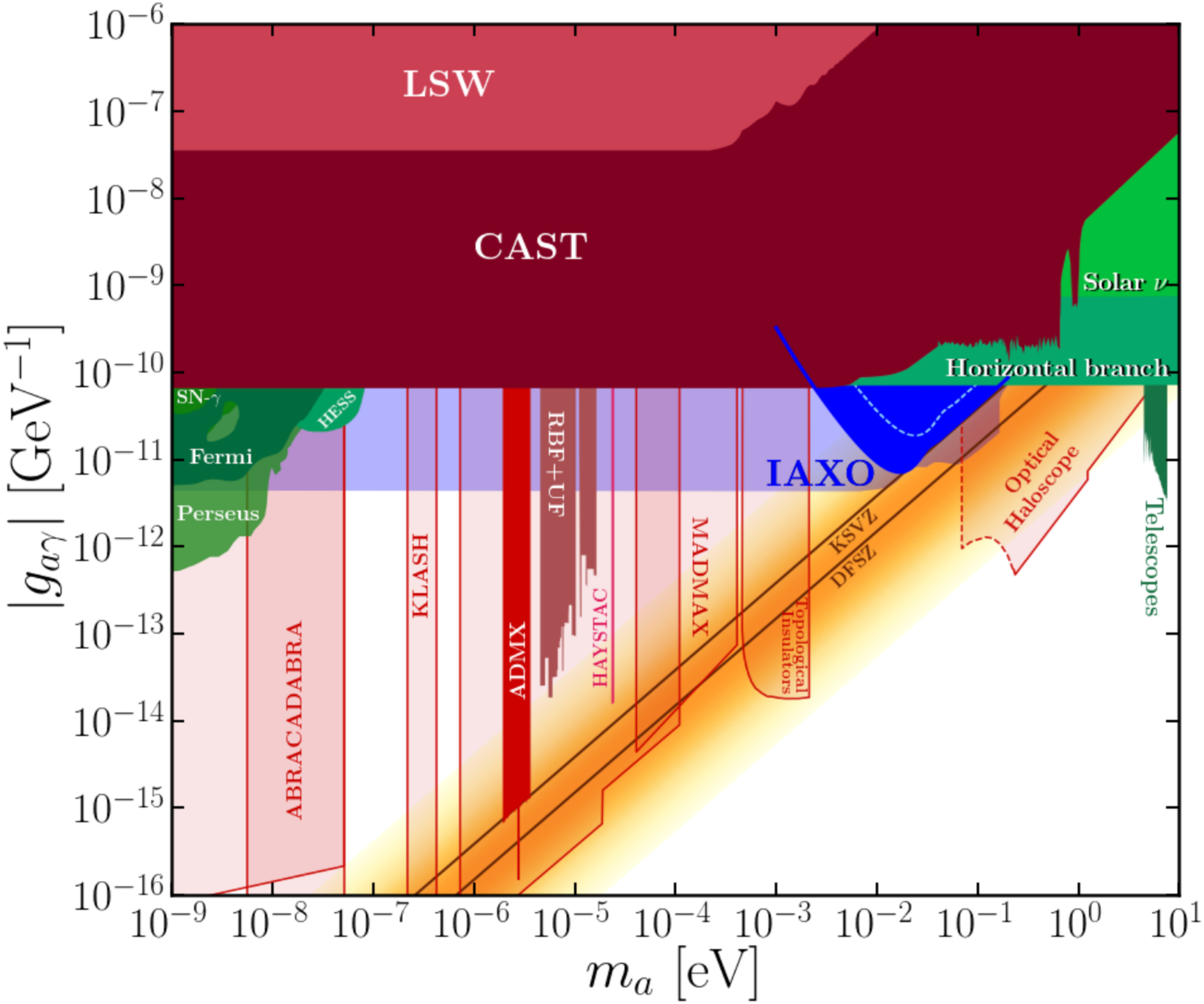
$$m_{b'}/m_{a'} \simeq r^{-1}(\Lambda_h/\Lambda_{\rm QCD})^2 \text{ and } g_{b\gamma\gamma} = g_{a\gamma\gamma} r^{-1}$$

$$m_{a'} = \Lambda_{\rm QCD}^2/F_a = (r/\sqrt{1+r^2}) m_a .$$

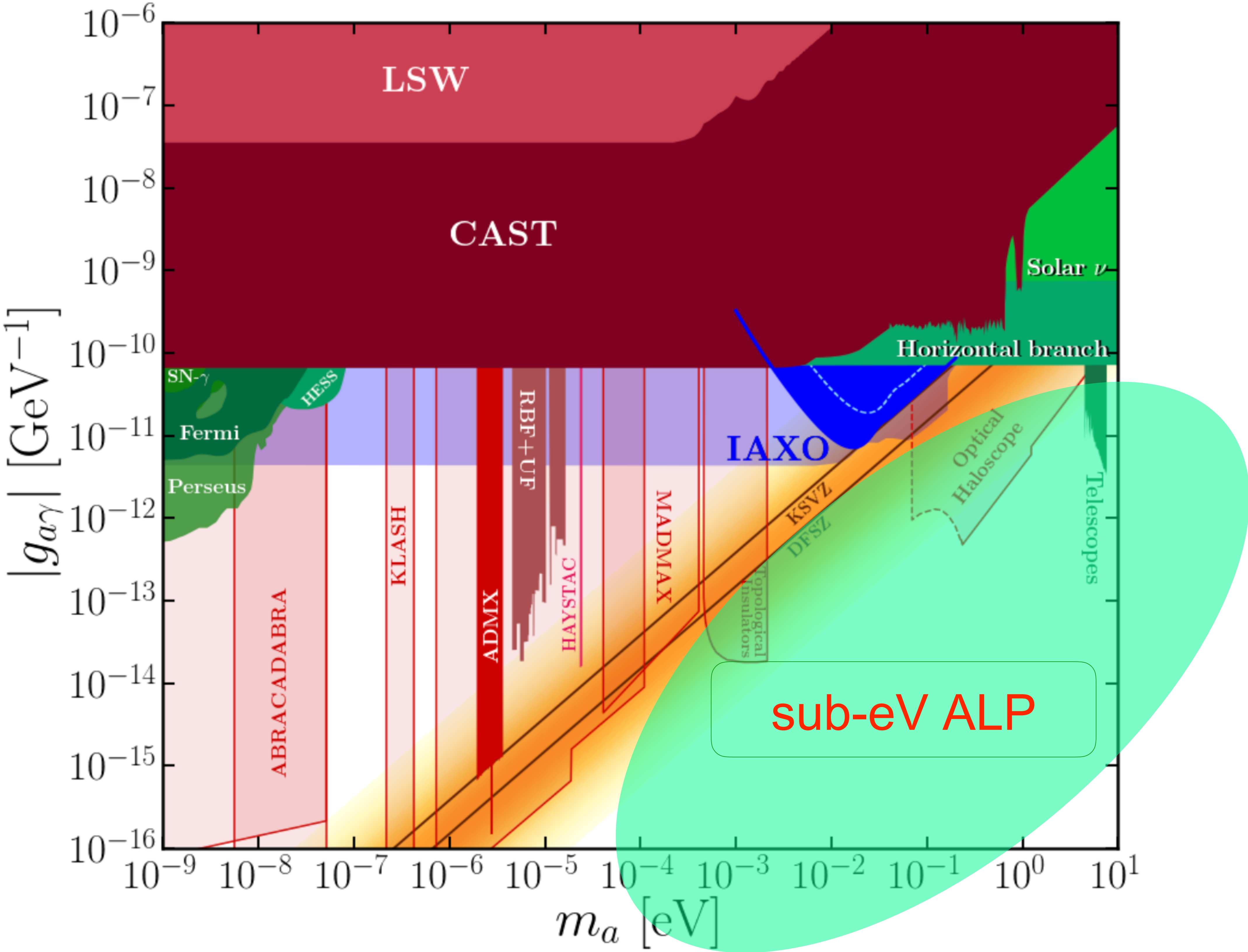
- For $\Lambda_{\rm QCD} < \Lambda_h \lesssim \sqrt{r}\, 10^{4.5}\,{\rm GeV}$, we can have sub-eV b-axion with $g_{b\gamma\gamma} \gg g_{a\gamma\gamma}$

- Motivates ALP search in $g_{a\gamma\gamma}$ below QCD axion band!

Implication: QCD axion, sub-eV ALP



Implication: QCD axion, sub-eV ALP



Implication: QCD axion, a heavy ALP

- $f_a \sim f_b \sim 10^{16}$GeV (string axion) → r~1 Svrcek, Witten 06

- $\Lambda_h > 10^{10}$GeV → $m_{b'}$ ~ TeV scale

- Decay of heavy b-axion can save string QCD axion from two cosmological tensions
  1. Too much abundance

$$\Omega_a h^2 \simeq (2 \times 10^4) \times \theta_{\rm i}^2 \times \left(\frac{F_a}{10^{16}\text{GeV}}\right)^{\frac{7}{6}}$$

  2. High scale inflation inconsistent with $P_{iso} < 0.038 \text{x} (2 \text{x} 10^{-9})$

$$H_I \lesssim 2.7 \times 10^{10}\text{GeV} \left(\frac{\theta_{\rm i}}{0.1}\right) \left(\frac{F_a}{10^{16}\text{GeV}}\right) \left(\frac{\Omega_{\rm CDM} h^2}{\Omega_a h^2}\right)$$

Implication: Quintessence axion

- Recently, non-vanishing rotation angle of CMB linear polarization was reported (isotropic birefringence)
  → β = (0.342 ± 0.09)deg (3.6σ) Minami, Komatsu 20

- A pseudo-scalar field A coupled to photon via

$$\mathcal{L}_{\rm eff} \supset -c_\gamma \frac{g_{\rm em}^2}{16\pi^2}\frac{A}{F_A}F^{\mu\nu}\tilde{F}_{\mu\nu}\,. \qquad g_{\phi\gamma} = \frac{c_\gamma \alpha_{\rm em}}{\pi F_A}$$

can induce β ≠ 0 Carroll, Field, Jackiw 90, Harari, Sikivie 92

$$\beta = 0.42\,{\rm deg} \times \frac{c_\gamma}{2\pi} \times \frac{A(t_0) - A(t_{\rm LSS})}{F_A}$$

Implication: Quintessence axion

- Quintessence axion can explain the non-zero β=O(0.1) (from an anomalous global $U(1)_X$)

$$\mathcal{L}_{\rm eff} \supset -c_\gamma \frac{g_{\rm em}^2}{16\pi^2}\frac{A}{F_A}F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{V_0}{2}\left[1-\cos\left(\frac{A}{F_A}\right)\right]$$

$$\beta = 0.42\,\mathrm{deg} \times \frac{c_\gamma}{2\pi} \times \frac{A(t_0)-A(t_{\rm LSS})}{F_A}$$

- $m_q \sim H_0 \sim 10^{-33}$eV for the slow-roll today
  → $f_q \sim M_P$ from $\Lambda_{DE}^2 = (2\mathrm{meV})^2 \sim m_q f_q$

- $\Delta q \sim O(0.1\text{-}1) f_q$ $\quad\quad$ $\delta q/f_q \propto \exp(M_P^2 H_0 t/f_q^2)$

- With $c_\gamma \sim O(1\text{-}10)$, can explain β=O(0.1)!

Implication: Quintessence axion

- Challenges of quintessence from $U(1)_X$
  (1) quality issue (why so small mass)
  (2) Why does the quintessence couple to $U(1)_{em}$?

Implication: Quintessence axion

- Challenges of quintessence from $U(1)_X$
  (1) quality issue (why so small mass)
  (2) Why does the quintessence couple to $U(1)_{em}$?

Contrived set-up for the fermions…

Implication: Quintessence axion

- Challenges of quintessence from $U(1)_X$
  (1) quality issue (why so small mass)
  (2) Why does the quintessence couple to $U(1)_{em}$?

- 2-form and 3-form gauge theory may resolve these issues simultaneously?

Implication: Quintessence axion

- Challenges of quintessence from $U(1)_X$
  (1) quality issue (why so small mass)
  (2) Why does the quintessence couple to $U(1)_{em}$?

- 2-form and 3-form gauge theory may resolve these issues simultaneously?

- The mixing among axions resulting from the Higgsing all the 3-forms
  → may induce the high quality quintessence coupling to $U(1)_{em}$

Implication: Quintessence axion

- Quintessence model

$$\Lambda_{\rm QCD} \leftrightarrow \Lambda_{\rm DE} \simeq 2{\rm meV} \qquad \theta_{\rm QCD} \leftrightarrow \theta_{\rm DE} \qquad f_a \leftrightarrow f_q \simeq M_P$$

$$m_a \leftrightarrow m_q \simeq H_0 \simeq 10^{-33}{\rm eV}$$

- Suppose both QCD axion and quintessence suffer from coupling to $P_{\mu\nu\lambda}$ ($\Lambda_h >> \Lambda_{QCD}$) with dP=S, $Z \equiv (1/4!)\epsilon^{\mu\nu\lambda\rho} S_{\mu\nu\lambda\rho}$

$$\begin{aligned}\mathcal{L}(C,E,P,a,q,b) \supset\ & -\frac{1}{2}X^2 - \frac{1}{2}Y^2 - \frac{1}{2}Z^2 \\ & + \ a m_a X + q m_q Y \\ & + \ (aM_a + qM_q + bM_b)Z\end{aligned}$$

Implication: Quintessence axion

- Diagonalizing mass matrix gives

$$a \approx \begin{cases} \frac{1}{\sqrt{2}}a' - \frac{f_a}{2f_q}q' + \frac{1}{\sqrt{2}}b' & \text{for } f_q \gg f_b \simeq f_a\,, \\ -\frac{f_a}{f_b}a' - \frac{f_a}{f_q}q' + b' & \text{for } f_q \gg f_b \gg f_a\,, \end{cases}$$

- QCD axion-SM photon coupling gives $-(g_{q\gamma\gamma}/2)q \wedge F^{\rm em} \wedge F^{\rm em}$ with $g_{q\gamma\gamma} = c_a \alpha_{em}/(2\pi f_q)$

- Cosmic birefringence due to quintessence

$$\beta = \frac{g_{q\gamma\gamma}}{2} \times [q(t_0) - q(t_{\rm LSS})]$$

$$\simeq 0.42\ \text{deg} \times \frac{c_a}{4\pi} \times \frac{q(t_0) - q(t_{\rm LSS})}{f_q}$$

Implication: Quintessence axion

- Diagonalizing mass matrix gives

$$a \approx \begin{cases} \frac{1}{\sqrt{2}}a' - \frac{f_a}{2f_q}q' + \frac{1}{\sqrt{2}}b' & \text{for } f_q \gg f_b \simeq f_a\,, \\ -\frac{f_a}{f_b}a' - \frac{f_a}{f_q}q' + b' & \text{for } f_q \gg f_b \gg f_a\,, \end{cases}$$

- QCD axion-SM photon coupling gives $-(g_{q\gamma\gamma}/2)q\wedge F^{\rm em}\wedge F^{\rm em}$ with $g_{q\gamma\gamma}=c_a\alpha_{em}/(2\pi f_q)$

- Cosmic birefringence due to quintessence

$$\beta = \frac{g_{q\gamma\gamma}}{2}\times[q(t_0)-q(t_{\rm LSS})]$$

$$\simeq 0.42\ {\rm deg}\times\frac{c_a}{4\pi}\times\frac{q(t_0)-q(t_{\rm LSS})}{f_q}$$

Ca=O(10), Δq/fq=O(1)
→ β=O(0.1)

Conclusion

- Quality issue still remains in the dual formulation
  → unique source → unique solution (better control than PQ)
  → hint for multiple axion scenario

- Implication for Pheno

Conclusion

- Quality issue still remains in the dual formulation
  → unique source → unique solution (better control than PQ)
  → hint for multiple axion scenario

- Implication for Pheno

Quality issue
→ coupling to extra 3-forms

Conclusion

- Quality issue still remains in the dual formulation
  → unique source → unique solution (better control than PQ)
  → hint for multiple axion scenario

- Implication for Pheno

Quality issue
→ coupling to extra 3-forms

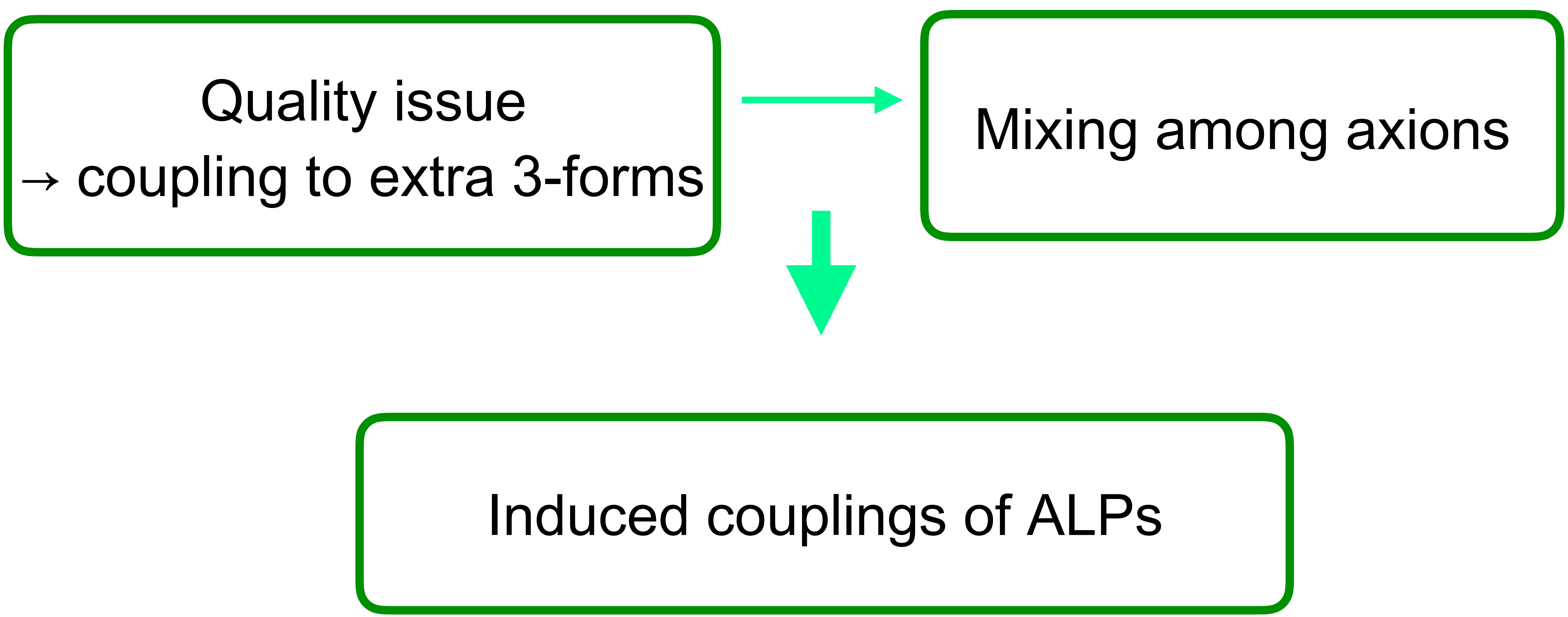
→

Mixing among axions

Conclusion

- Quality issue still remains in the dual formulation
  → unique source → unique solution (better control than PQ)
  → hint for multiple axion scenario

- Implication for Pheno



Conclusion

- Quality issue still remains in the dual formulation
  → unique source → unique solution (better control than PQ)
  → hint for multiple axion scenario

- Implication for Pheno (Correlating Quality with ALP pheno)