Heavy (Dynamical) Axions

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Based on arXiv:1805.06465
In collaboration with: *M. K. Gaillard, M. B. Gavela, R. Houtz and R. del Rey*
Seminar - Kavli IPMU, Japan
July 6th, 2018

Outline

1. Strong CP and axion solution
2. Heavy axion models
3. Small-size instantons
4. Massless quark: dynamical axion
5. Colour Unified Dynamical Axion

Why axion?

Strong CP problem

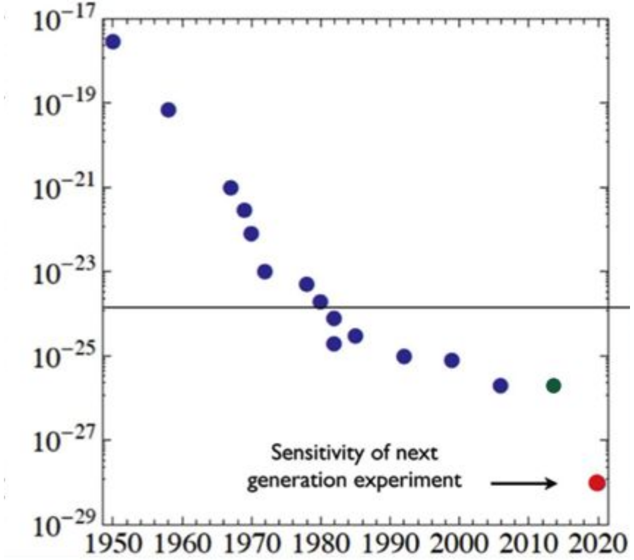
$$\mathcal{L}_{QCD} \supset \mathcal{L}_{\cancel{CP}} = -\bar{q} m e^{i\beta} q + \theta_{QCD} \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

One physical CPV phase: $\bar{\theta} = \theta_{QCD} + \arg\det M$

$$d_n \approx 10^{-16}|\bar{\theta}|\mathrm{e}\cdot\mathrm{cm} \qquad \bar{\theta} \lesssim 10^{-10}$$

Why is it so small?

Neutron EDM (Electric Dipole Moment)



[B.Fillipone via diLuzio]

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Strong CP ~~problem~~ hint

$\mathcal{L}_{QCD}$

One physi

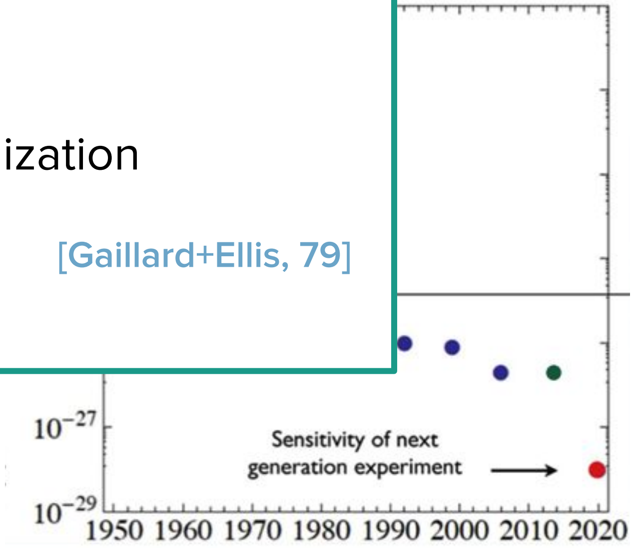
- ➔ Fine-tuning
- ➔ $\bar{\theta} = 0$ harmless under renormalization

[Gaillard+Ellis, 79]

$d_n \approx 10^{-16}|\theta|\mathrm{e}\cdot\mathrm{cm}$ $\theta \lesssim 10^{-10}$

Why is it so small?

Neutron EDM (Electric Dipole Moment)



[B.Fillipone via diLuzio]

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The axion solution

- ➔ If $\bar{\theta}$ were a scalar field, its vev would be zero [Vafa+Witten, 84]

$$\bar{\theta}\,\frac{\alpha_s}{8\pi}G\tilde{G} \quad \longrightarrow \quad \left(\bar{\theta}-\frac{a}{f_a}\right)\frac{\alpha_s}{8\pi}G\tilde{G}$$

- ➔ Introduce a $U(1)_{PQ}$ symmetry (classically exact): [Peccei+Quinn 77]
  - ◆ Spontaneously broken $\longrightarrow$ pGoldstone Boson: AXION
  - ◆ Anomalous: explicitly broken by QCD instantons $\longrightarrow$ massive

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My definition of axion:

“Any pseudo-Goldstone Boson of a global U(1) symmetry, which is exact at the classical level but explicitly broken by instantons”

Invisible axion mass

- ➔ Any model were the only $\cancel{PQ}$ are QCD instantons:

$$m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

- ➔ Why does it vanish for $m_u \longrightarrow 0?$
- ➔ Both η' and axion couple to instantons:

$$\frac{\alpha}{8\pi}\left(2\frac{\eta'}{f_\pi} - \frac{a}{f_a}\right)\tilde{G}G \quad \longrightarrow \quad m^2_{\eta'_{phys}} = \frac{2\Lambda^4_{QCD}}{f_\pi^2}$$

- ➔ Physical axion: orthogonal combination

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Invisible axion mass

- Any model were the only $\cancel{PQ}$ are QCD instantons:

- One source of $\cancel{PQ}$
- Two anomalous pseudoscalars: a, η'

One must remain light

- Physical axion: orthogonal combination

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Invisible axion couplings

- ➔ KSVZ: PQ implemented with exotic vectorial quarks and a scalar
- ➔ DFSZ: PQ implemented with 2HDM + scalar
- ➔ Couplings: $\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a} \qquad \Longrightarrow \qquad g_{a\gamma\gamma} \propto m_a$$

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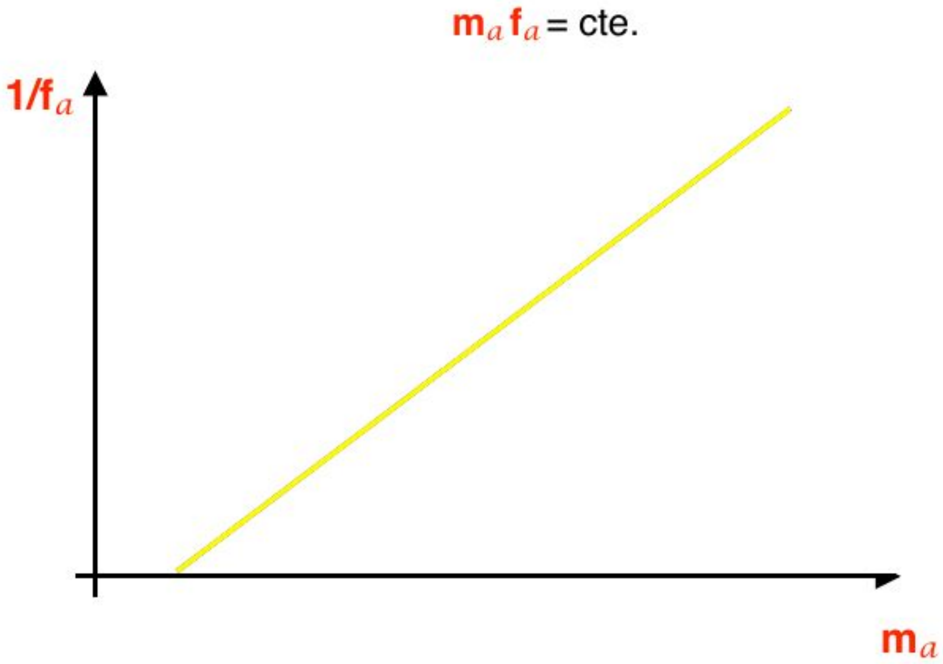
Invisible axion parameter space



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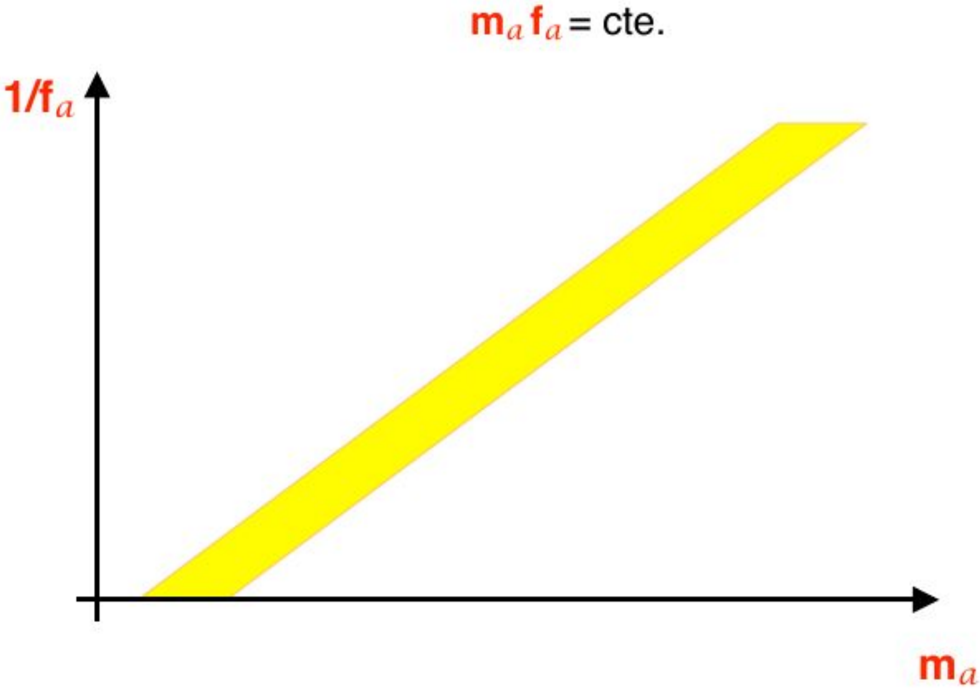
Invisible axion parameter space



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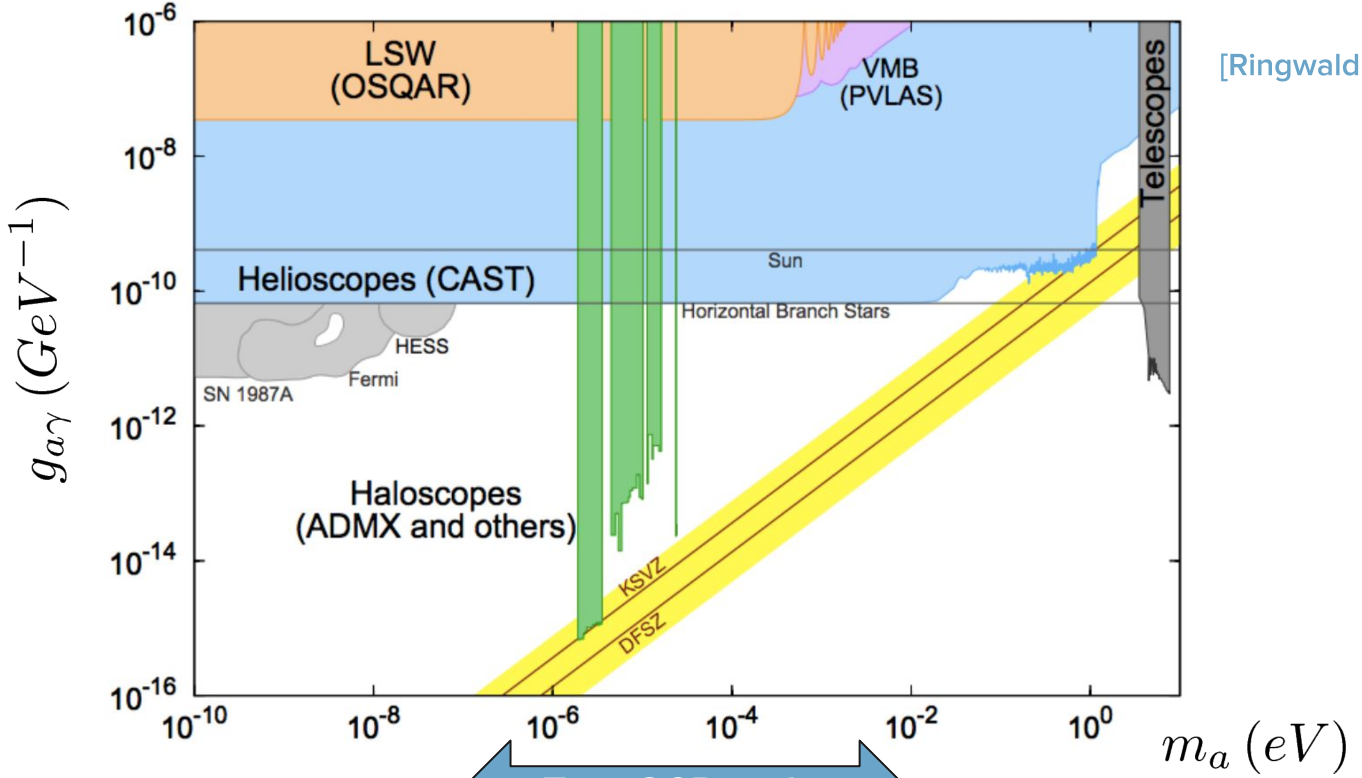
Invisible axion parameter space



[Ringwald, PDG 17]

True QCD region

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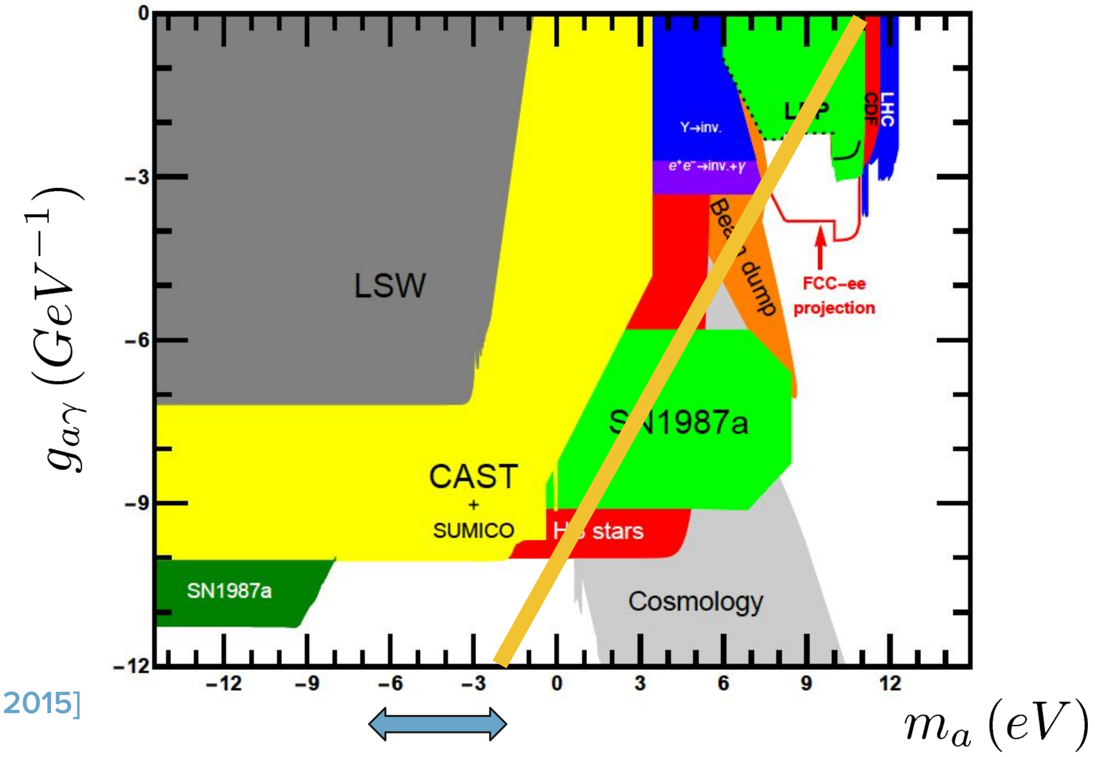
Invisible axion parameter space



[Jaeckel+ Spannowsky 2015]

True QCD region

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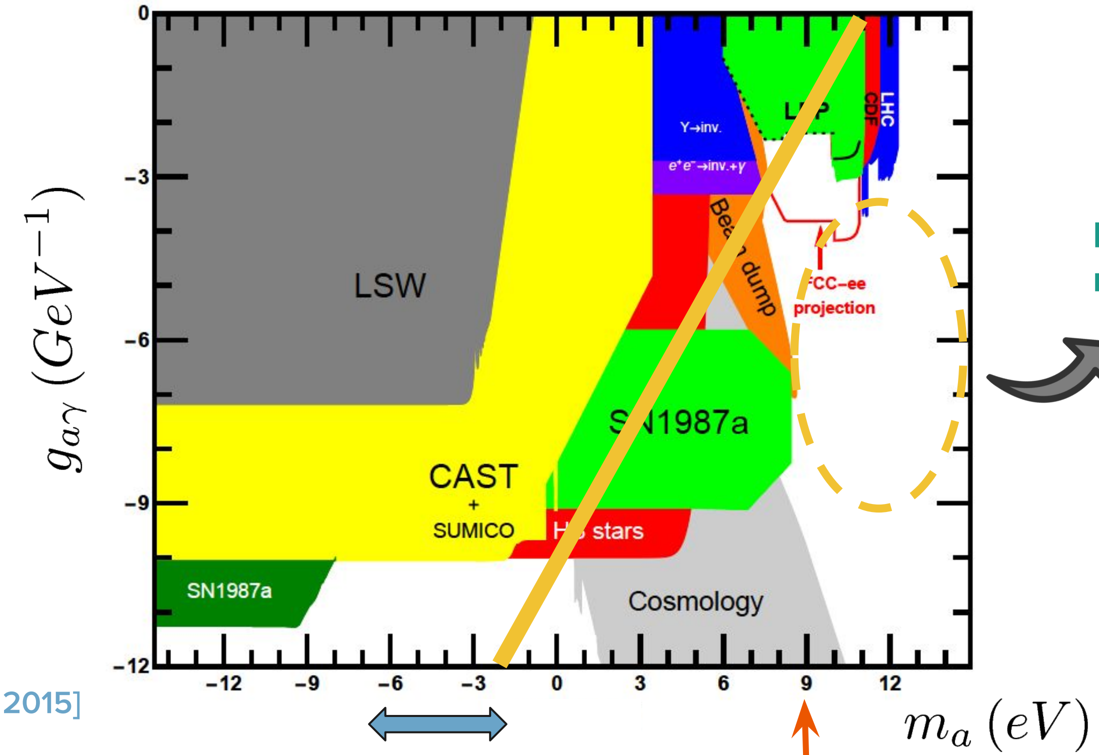
Invisible axion parameter space



[Jaeckel+ Spannowsky 2015]

Does the “true” QCD region amplify?

True QCD region

TeV

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Can we make it heavy?

How many light axions has your theory?

Compare the number of:

Anomalous pseudoscalars:

$$\eta'_{QCD},\ a_1,\ a_2 \ldots$$

VS

PQV instanton sources

$$G_c\tilde{G}_c,\ G_1\tilde{G}_1,\ G_2\tilde{G}_2 \ldots$$

Heavy axion models

- ➔ New strong interactions with scale Λ'

$$\frac{\alpha}{8\pi}\frac{a}{f_a}\tilde{G}G+\frac{\alpha'}{8\pi}\frac{a}{f_a}\tilde{G}'G' \quad \begin{cases} m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 + \Lambda'^4 & \text{(no light q')} \\ m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 + m_\pi'^2 f_\pi'^2 & \text{(with light q')} \end{cases}$$

- ➔ New confining group → New theta
- ➔ Need some larger symmetry to align them:
  - ◆ Z2
  - ◆ Unification

[Rubakov, 97]
[Berezhiani et al ,01]
[Fukuda et al, 01]
[Hsu et al, 04]
[Hook et al, 14]
[Chiang et al, 16]
[Khobadize et al,]
[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]

arXiv:1805.06465

Heavy axion models

→ New strong interactions with scale Λ'

$\frac{\alpha}{8\pi}$

o light q')

ith light q')

→

→

,01]

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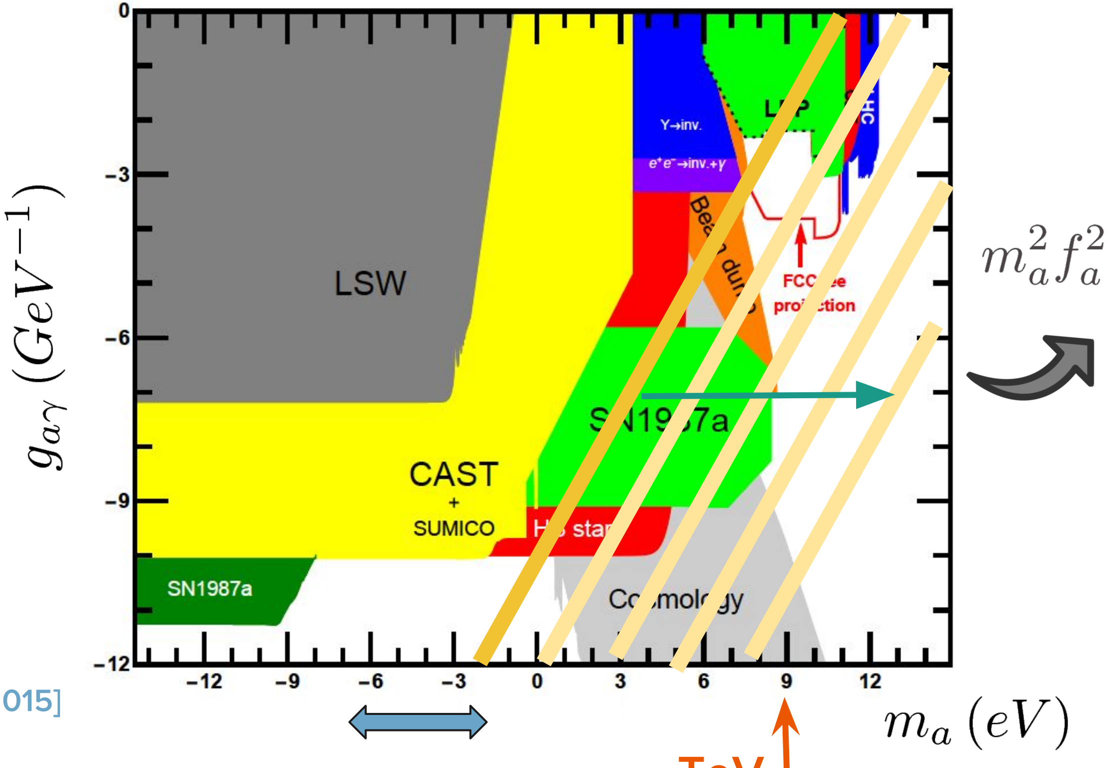
◆ Z2

◆ Unification

$$m_a^2 f_a^2 \sim \text{LARGE const}$$

[Chiang et al, 16]
[Khobadize et al,]
[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]

Invisible axion parameter space



$$m_a^2 f_a^2 \sim \text{LARGE const}$$

[Jaeckel+ Spannowsky 2015]

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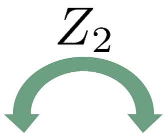
SU(5) mirror world PQWW axion

[Rubakov, 97]



- ➔ SU(5)xSU(5)’ ➔ $\theta = \theta'$
- ➔ 2HDM in each world
- ➔ One shared U(1)PQ through Scalar connecting both worlds
- ➔ CONS: tuning in the scalar sector

$$M_a \sim \left(\frac{\Lambda_{mc}}{\Lambda_{QCD}}\right)^{\frac{3}{2}} \cdot \left(\frac{v}{v_m}\right)^{\frac{1}{2}} \cdot m_{WW} \qquad \sim GeV - TeV$$

- ➔ Berherziani et al, 01 did it for the SM gauge group

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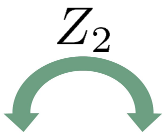
Visible heavy QCD axion

[Fukuda+Harigaya+Ibe+Yanagida 01]



- ➔ SMxSM’ ➔ theta=theta’
- ➔ Exotic vectorial fermions ➔ KSVZ
- ➔ Nice cosmology, several DM candidates:

$$m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2 + m_\pi'^2 f_\pi'^2$$

Gherghetta+Nagata+Shifman 16

- $\mathrm{SU}(3+N') \to \mathrm{SU}(3)_c \times \mathrm{SU}(N')$
- Exotic vectorial fermions → KSVZ
- PROS: less matter content
- CONS: mass splitting of unified partners
  - Need to further enlarge the gauge group and <u>assume no extra CP phase</u>

$$SU(N') \times SU(3+N') \longrightarrow SU(N') \times SU(3)_c$$

Small Size Instantons

Extra source of axion mass

Heavy axion: Small Size Instantons

- ➔ Typically, at high energies (= small size) couplings are very small.
- ➔ The instanton density has an exponential suppression:

$$D[\alpha'(\mu)] \propto e^{-2\pi/\alpha'(\mu)}$$

Usually sizable only at the confinement scale

$$\left(e^{-2\pi/0.1} \sim 10^{-28}\right)$$

- ➔ New Physics can change the RG flow and induce a new source of axion mass

[Holdom+Peskin, 82]
[Dine+Seiberg, 86]
[Agrawal+Howe, 17]
[Flynn+Randall, 87]

- ➔ Large coupling
- ➔ At some Large scale

$$\Lambda^4_{SSI} \sim \mu^4 \, e^{-2\pi/\alpha}$$

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Heavy axion: Small Size Instantons

- ➔ Typically, at high energies (= small size) couplings are very small.
- ➔ The instanton density has an exponential suppression:

$^{-28})$

- ➔ New P

skin, 82]
g, 86]
we, 17]
all, 87]

$$\Lambda_{SSI}^4 \sim \mu^4 \, e^{-2\pi/\alpha}$$

- ➔ Large coupling
- ➔ At some Large scale μ

New sizable contribution to the axion mass!!

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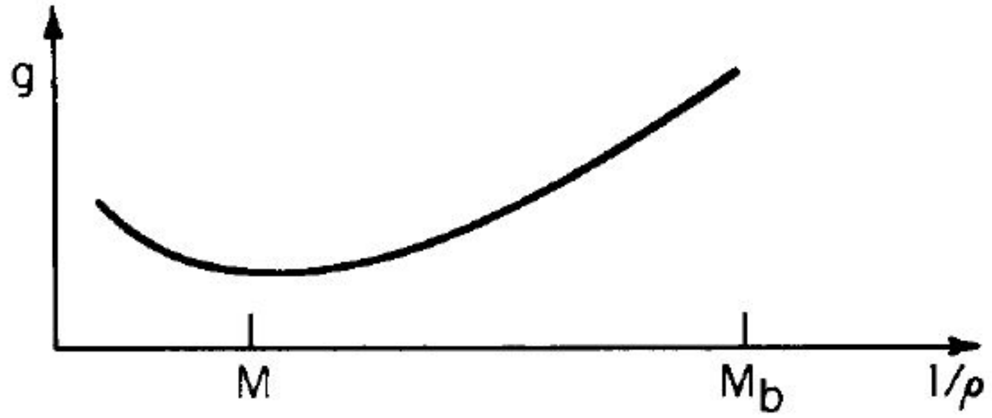
Small Size Instanton: Randall and Flynn, 87

- ➔ Extra coloured fermions/scalars
- ➔ Change the sign of the beta function



[Flynn+Randall, 87]

Factoring the strong CP problem

[Agrawal+Howe, 17]

$$SU(3)_1 \times SU(3)_2 \to SU(3)_c$$

$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_{s_1}(\mu)} + \frac{1}{\alpha_{s_2}(\mu)}, \qquad \mu = M,$$

- ➔ 2 axions up to 1000 times heavier than invisible axion
- ➔ Some tuning in the couplings is required

[Flynn+Randall, 87]

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Massless quark solution

Dynamical axion

Massless quark solution

- ➔ Under a chiral rotation: $U(1)_A : \quad q \to e^{\frac{\alpha}{2} i\gamma_5} q$

$$\mathcal{L} \supset -m_q \bar{q} q - \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow -m_q \bar{q} e^{i\alpha\gamma_5} q - (\theta - \alpha) \frac{\alpha_s}{8\pi} G\tilde{G}$$

- ➔ If $m_q = 0,$ the phase θ can be fully reabsorbed $\Longrightarrow$ **Strong CP Problem solved!**

- ➔ No different from usual PQ solution [Peccei+Quinn 77]

- ➔ Most economical option: Massless up quark, disfavored by lattice data [Manohar et al 16, PDG]

Dynamical Axion

[Choi+Kim 85]

- ➔ Exotic massless quark ψ **How do we hide it?**
- ➔ New confining group $\tilde{\Lambda} \gg \Lambda_{QCD}$
  - ◆ **Problem:** new CP violating phase $\tilde{\theta}$
  - ◆ **Solution:** Add another massless quark χ

	$SU(3)_c$	$SU(\tilde{N})$
ψ	$\square$	$\square$
χ	1	$\square$

Massless quark content

- ➔ $SU(\tilde{N})$ Confines + Chiral Symmetry Breaking: $U(4)_L \times U(4)_R \xrightarrow[\langle\bar{\psi}\psi\rangle]{\langle\bar{\chi}\chi\rangle} U(4)_V$

pseudo-Goldstone Bosons (pGB): $16 = 8 + 3 + \bar{3} + \boxed{1 + 1}$

The η' become dynamical axions

Dynamical Axion: masses

[Choi+Kim 85]

- ➔ Two axions: a1 = ($\bar{\psi}\psi$)   a2= ($\bar{\chi}\chi$)

$$2\,\cancel{PQ}\ \text{instantons}\ \begin{cases} \Lambda_{QCD} \\ \tilde{\Lambda} \end{cases} \qquad VS \qquad 3\ \text{pseudoscalars}\ \begin{cases} \bar{\psi}\psi \\ \bar{\chi}\chi \\ \eta'_{QCD} \end{cases}$$

- ➔ **One axion remains light:**

$$m_{a_1}^2 f_a^2 \sim \tilde{\Lambda}^4 \qquad m_{\eta'}^2 f_\pi^2 \sim \Lambda_{QCD}^4 \qquad m_{a_2}^2 f_a^2 \sim m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

UV completion of a usual invisible axion

Why dynamical?

Colour Unified Dynamical Axion

M. K. Gaillard, M. B. Gavela, R. Houtz, P.Q. and R. del Rey

First colour-unified model with massless quarks

arXiv:1805.06465

Color Unified Dynamical Axion

➔ Unification allows to identify the two phases: only one massless quark needed

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(\tilde{3}) \times U(1)$$

$$\theta_6 = \theta_c = \tilde{\theta}$$

Bellow unification scale:

	$SU(3)_c$	$SU(\tilde{3})$
ψ_L	$\square$	$\bar{\square}$
ψ_L^c	$\bar{\square}$	$\square$
$2 \times \psi_\nu$	1	1

Over Unification scale:

	$SU(6)$	$SU(2)_L$	$U(1)$
Ψ_L	20	1	0

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Color Unified Dynamical Axion

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(\tilde{3}) \times U(1)$$

➔ SM quarks are embedded in fundamentals of SU(6)

SM

$$Q_L \equiv (q\,, \tilde{q})_L\,, \quad U \equiv (u\,, \tilde{u})_R\,, \quad D \equiv (d\,, \tilde{d})_R$$

Problem: How do we give large masses to the unified partners?

1. Without spoiling SM quark masses
2. Without breaking EW at a high scale
3. In order to separate the running of the two groups .

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Color Unified Dynamical Axion: The real thing

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}$$

SM

$$Q_L \equiv (q\,,\,\tilde{q})_L$$

- ➔ Spontaneously broken by the vev of Δ

$$\langle \Delta \rangle = \Lambda_{\rm CUT} \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

q'_L Extra primed quarks

$$\kappa_q \, q'_L \Delta^* Q_L \longrightarrow \Lambda_{\rm CUT} \, \kappa_q \, q'_L \tilde{q}_L$$

$$(6,1)\;(\bar{6},3)\;(1,\bar{3})$$

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Color Unified Dynamical Axion: The real thing

$$SU(6)\times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}$$

➔ Spontane

$$\tilde{q})_L$$

$$\langle\Delta\rangle =$$

ed quarks

Allows for a large mass for the tilde sector without spoiling the SM quark masses

$$\kappa_q\, q'_L \Delta^* Q_L \longrightarrow \Lambda_{\rm CUT}\,\kappa_q\, q'_L \tilde{q}_L$$

$$(6,1)\;(\bar{6},3)\;(1,\bar{3})$$

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Color Unified Dynamical Axion

$$SU(6) \times SU(3')$$

$$\theta_6 \qquad\qquad \theta'$$

Two massless fermions to reabsorb both CP phases

	$SU(6)$	$SU(3)'$
ψ	20	1
χ	1	$\square$

	$SU(3)_c$	$SU(3)_{\text{diag}}$
ψ	$\square$	$\square$
χ	1	$\square$

→ Two dynamical axions $\eta'_\psi = (\bar{\psi}\psi)$ $\eta'_\chi = (\bar{\chi}\chi)$

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Running of the gauge couplings

- ➔ At the breaking scale:

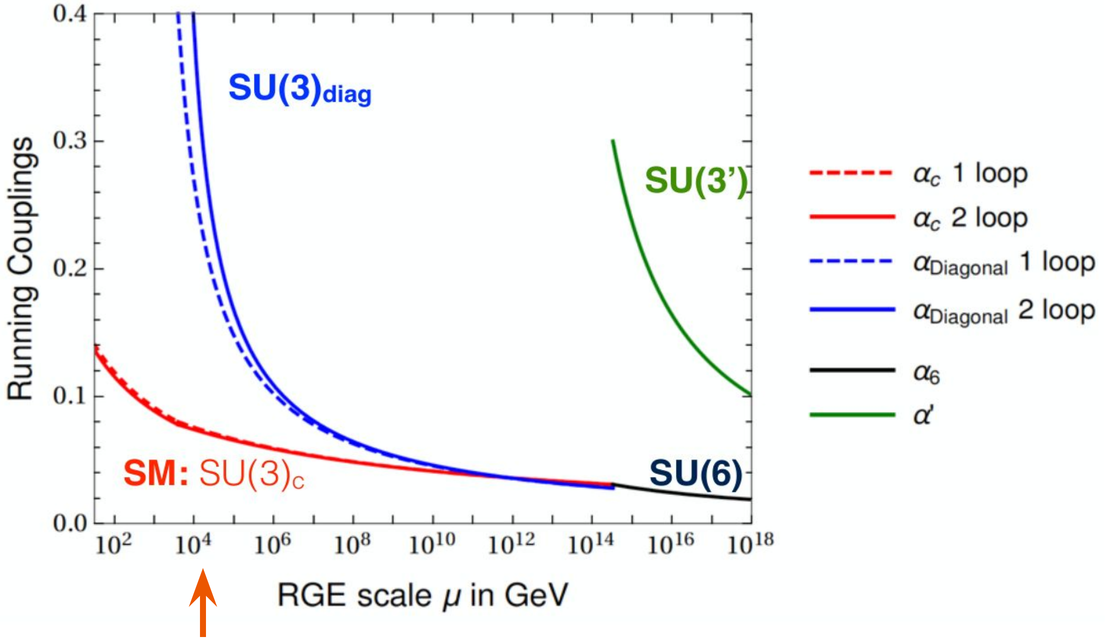
$$\frac{1}{\alpha_{\rm diag}(\mu)} = \frac{1}{\alpha_6(\mu)} + \frac{1}{\alpha'(\mu)}$$

$$\alpha_c(\Lambda_{\rm CUT}) = \alpha_6(\Lambda_{\rm CUT})$$

$SU(3)_{\rm diag}$ **confines before QCD**

$$\Lambda_{\rm d} \gg \Lambda_{QCD}$$

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}$$



10 TeV

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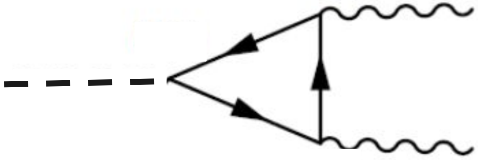
The anomalous pseudoscalars: dynamical axions + η'

➔ Anomalous currents $\Longrightarrow$ Anomalous couplings of the pseudoscalars:

$$j^{\mu}_{\psi_A} = \bar{\psi}\gamma^{\mu}\gamma^5\psi \equiv f_{\rm d}\,\partial^{\mu}\eta'_{\psi}\,,$$
$$j^{\mu}_{\chi_A} = \bar{\chi}\gamma^{\mu}\gamma^5\chi \equiv f_{\rm d}\,\partial^{\mu}\eta'_{\chi}\,,$$



$$\mathcal{L} \supset -\frac{\alpha_c}{8\pi}\frac{\sqrt{6}\,\eta'_{\psi}}{f_{\rm d}}G_c\tilde{G}_c - \frac{\alpha_{\rm diag}}{8\pi}\left(2\,\frac{\eta'_{\chi}}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_{\psi}}{f_{\rm d}}\right)G_{\rm diag}\tilde{G}_{\rm diag}$$

Confinement

$$\mathcal{L} \supset \Lambda^4_{\rm diag}\,\cos\left(2\,\frac{\eta'_{\chi}}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_{\psi}}{f_{\rm d}}\right) + \Lambda^4_{\rm QCD}\,\cos\left(2\,\frac{\eta'_{\rm QCD}}{f_{\pi}} + \sqrt{6}\,\frac{\eta'_{\psi}}{f_{\rm d}}\right)$$

Incorporating η'_{QCD}

- ➔ 3 anomalous pseudoscalars
- ➔ 2 sources of mass/breaking

Another light axion model?

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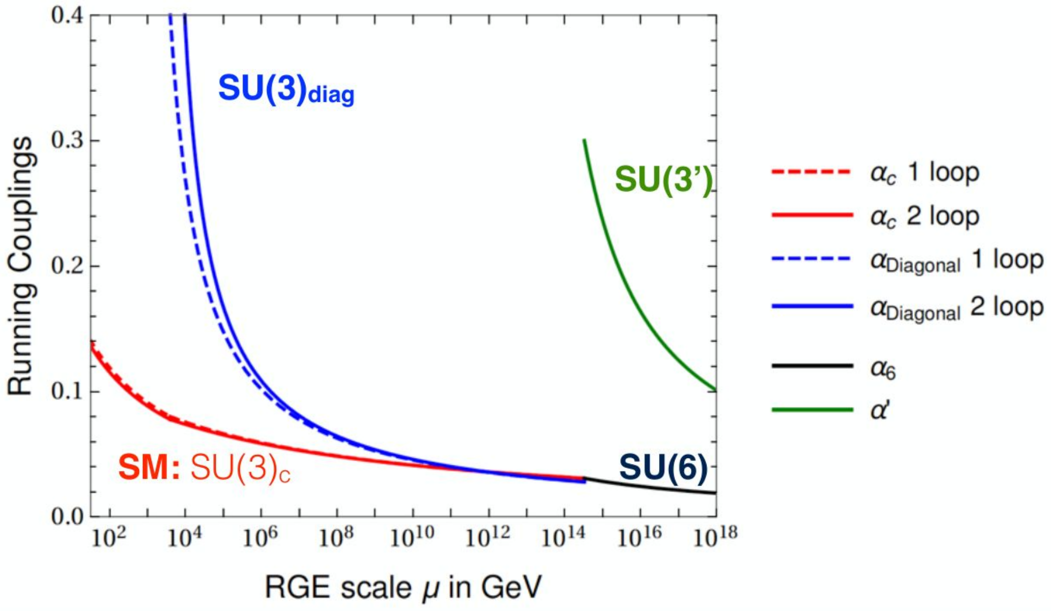
Small Size Instantons and axion mass



- ➔ Large coupling $\alpha' \sim 0.3$
- ➔ Large breaking scale

$$\Lambda_{CUT} \sim 10^{14-18}\, GeV$$

New sizable contribution to the axion mass!!

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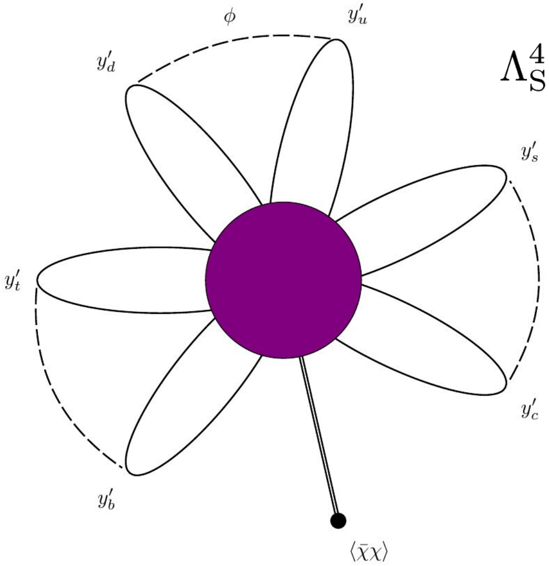
Small Size Instantons and axion mass

[t'Hooft, 73]
[Callan+Dashen+Gross, 77]
[Shifman+Vainshtein+Zakharov, 80]

- ➔ Dilute Instanton Gas approximation:



$$\Lambda^4_{\rm SSI} = -\underbrace{C_{inst}\int\frac{d\rho}{\rho^5}\left(\frac{2\pi}{\alpha'(\rho)}\right)^{2N_c} e^{-2\pi/\alpha'(\rho)}}_{\text{Pure Yang-Mills Instanton}}\underbrace{\left(\frac{2}{3}\pi^2\rho^3\left\langle\bar{\chi}\chi\right\rangle\right)\frac{1}{(4\pi)^6}\prod_i y'^{\,i}_u y'^{\,i}_d}_{\text{Fermionic suppression}}$$

$$\mathcal{L}_{eff} = \Lambda^4_{\rm SSI}\,\cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}}\right)$$

$$\Lambda_{SSI} \gtrsim 20\,TeV$$

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Dynamical axion potential and masses

$$\mathcal{L}_{eff} = \underbrace{\Lambda^4_{\rm SSI}\,\cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}}\right)}_{SU(3')\ \text{SSI Instantons}} + \underbrace{\Lambda^4_{\rm diag}\,\cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)}_{SU(3)_{\rm diag}\ \text{Instantons at conf.}} + \underbrace{\Lambda^4_{\rm QCD}\,\cos\left(2\,\frac{\eta'_{\rm QCD}}{f_\pi} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)}_{SU(3)_{\rm c}\ \text{Instantons at conf.}}$$

$$M^2_{\eta'_\chi,\,\eta'_\psi,\,\eta'_{\rm QCD}} = \begin{pmatrix} 4\,\frac{\left(\Lambda^4_{\rm SSI}+\Lambda^4_d\right)}{f^2_{\rm d}} & 2\sqrt{6}\,\frac{\Lambda^4_d}{f^2_d} & 0 \\ 2\sqrt{6}\,\frac{\Lambda^4_d}{f^2_d} & 6\,\frac{\left(\Lambda^4_d+\Lambda^4_{\rm QCD}\right)}{f^2_{\rm d}} & 2\sqrt{6}\,\frac{\Lambda^4_{\rm QCD}}{f_\pi\, f_{\rm d}} \\ 0 & 2\sqrt{6}\,\frac{\Lambda^4_{\rm QCD}}{f_\pi\, f_{\rm d}} & 4\,\frac{\Lambda^4_{\rm QCD}}{f^2_\pi} \end{pmatrix}$$

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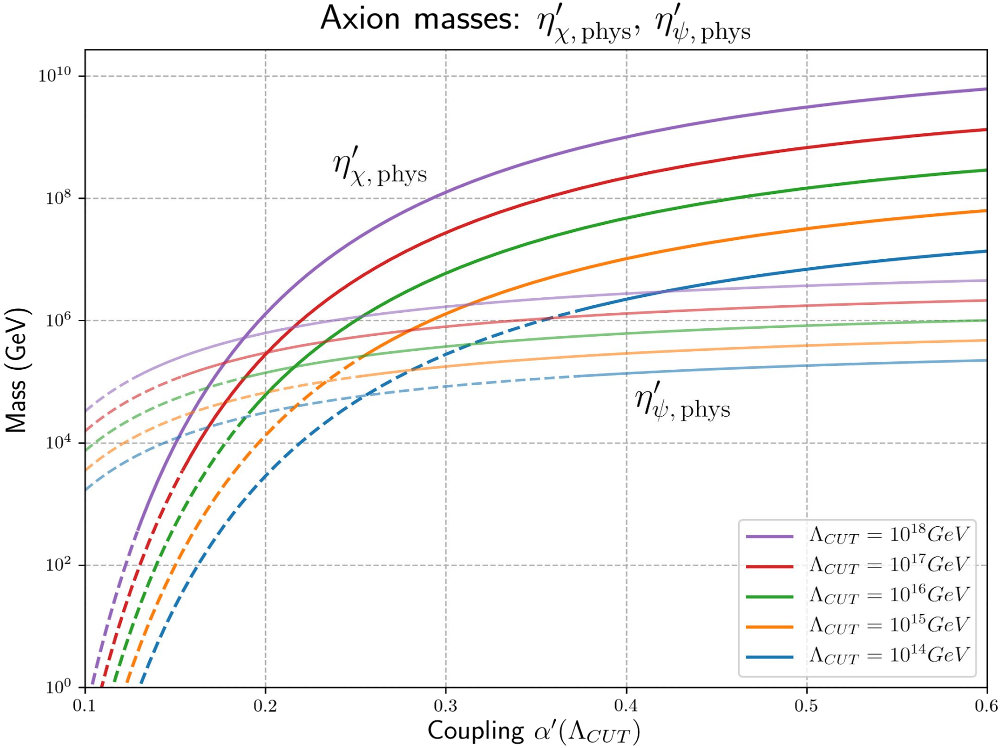
Dynamical axion masses



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Solution to the Strong CP problem

- ➔ Any source of axion mass breaks the PQ symmetry, **do SSI spoil the Strong CP solution?**
- ➔ Breaking pattern imposes:

$$\mathcal{L} \supset \bar{\theta}_6 \, \frac{\alpha_6}{8\pi} G_6 \tilde{G}_6 + \bar{\theta}' \, \frac{\alpha'}{8\pi} G' \tilde{G}' \longrightarrow (\bar{\theta}_6 + \bar{\theta}') \, \frac{\alpha_{\rm diag}}{8\pi} G_{\rm diag} \tilde{G}_{\rm diag} + \bar{\theta}_6 \, \frac{\alpha_c}{8\pi} G_c \tilde{G}_c$$

- ➔ Therefore the potential reads:

$$\mathcal{L}_{eff} = \Lambda^4_{\rm SSI} \, \cos\left(-2\,\frac{\eta'_\chi}{f_{\rm d}} + \bar{\theta}'\right) + \Lambda^4_{\rm diag} \, \cos\left(-2\,\frac{\eta'_\chi}{f_{\rm d}} - \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}} + \bar{\theta}' + \bar{\theta}_6\right) + \Lambda^4_{\rm QCD} \, \cos\left(-\sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}} + \bar{\theta}_6\right)$$

- ➔ The alignment of the 3 terms in the potential result in a CP-conserving minimum

$$\left\langle \bar{\theta}' - 2\,\frac{\eta'_\chi}{f_{\rm d}} \right\rangle = 0\,, \qquad \left\langle \bar{\theta}_6 - \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}} \right\rangle = 0$$

Strong CP problem solved

arXiv:1805.06465

Confinement and χSB of the SU(3)$_{\rm diag}$

- ➔ Chiral symmetry breaking by the condensates: $\langle\bar{\psi}\psi\rangle,\ \langle\bar{\chi}\chi\rangle$

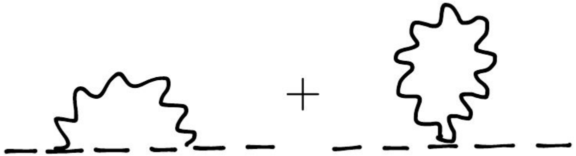
	$SU(3)_c$	$SU(3)_{\rm diag}$
ψ	$\square$	$\square$
χ	1	$\square$

$$U(4)_L \times U(4)_R \xrightarrow{\Lambda_d} U(4)_V$$

- ➔ Results in 16 pGB's: $16 = 8_c + 3_c + \bar{3}_c + \boxed{1_c + 1_c}$

become dynamical axions

- ➔ The "axipions", through quadratically divergent gluon loops, get a large mass:



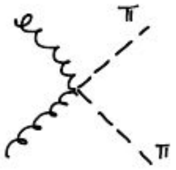
$$\Rightarrow \quad m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\rm diag} \qquad \bar{\psi}t^a\psi,$$

$$m^2(3_c) \approx \frac{\alpha_c}{\pi}\Lambda^2_{\rm diag} \qquad \bar{\psi}\chi,\ \bar{\chi}\psi$$

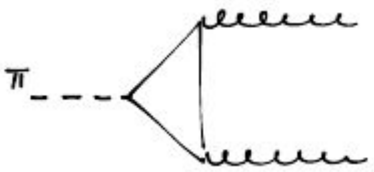
arXiv:1805.06465

Low energy Spectrum and Phenomenology

- ➔ No light axion.
  - ◆ Both axions too heavy for colliders
- ➔ Sterile fermions ψ_ν with couplings suppressed by Λ_{CUT} (basically invisible)
- ➔ QCD Coloured "axipions" are collider accessible, octets:



Pair produced



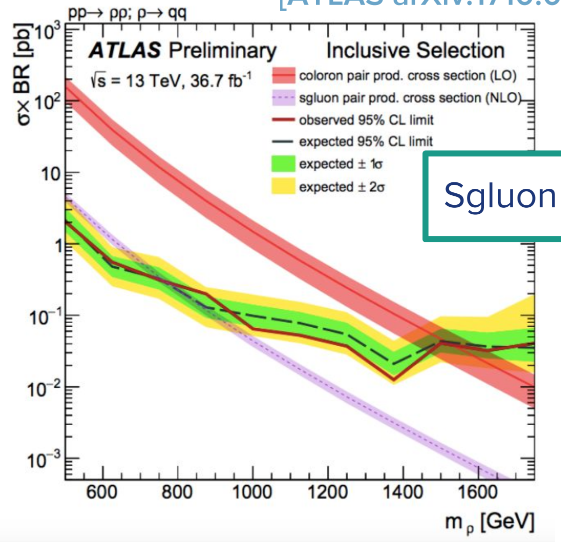
Anomalous decay

$$m(8_c) \gtrsim 770\, GeV$$

$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\mathrm{diag}}$$

$$\boxed{\Lambda_{\mathrm{diag}} \gtrsim 3\,\mathrm{TeV}}$$

[ATLAS arXiv:1710.07171]



Sgluon search

arXiv:1805.06465

Color Unified Dynamical Axion: model II

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(\tilde{3}) \times U(1)$$

Instead of adding a second massless fermion:

Model I

	$SU(6)$	$SU(3)'$
ψ	20	1
χ	1	$\Box$

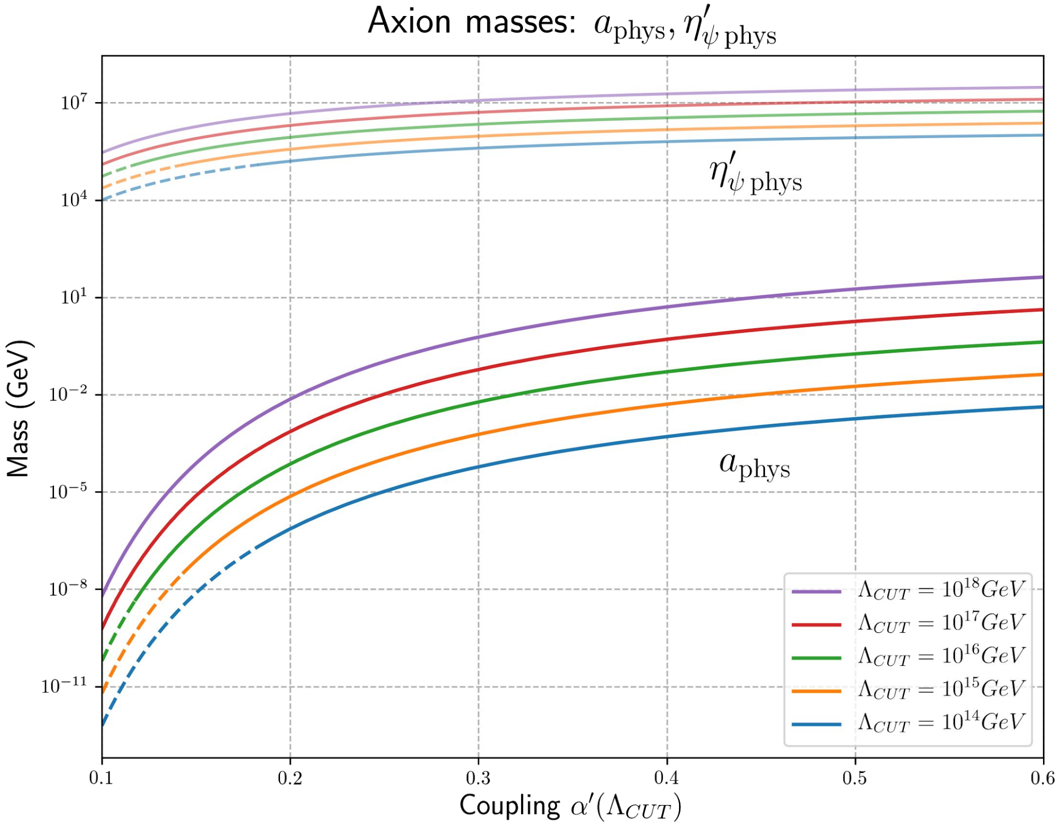
We added a second scalar Δ_2

Model II

	$SU(6)$	$SU(3)'$
ψ	20	1
Δ_2	$\Box$	$\overline{\Box}$

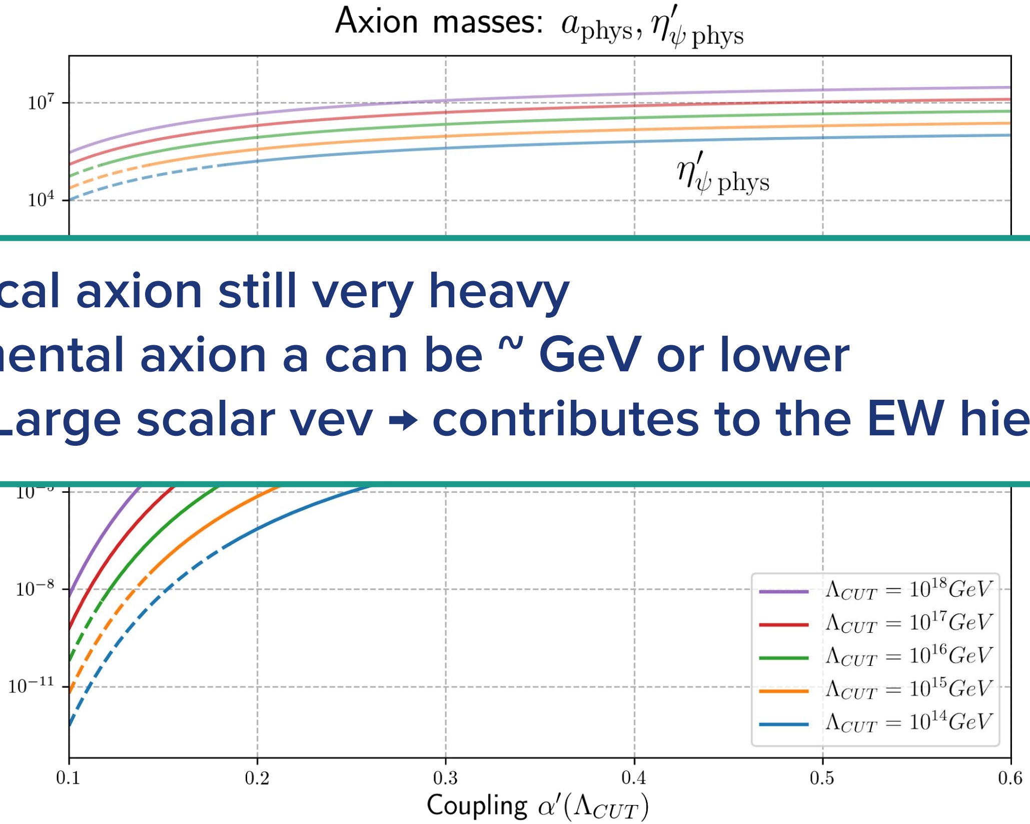
arXiv:1805.06465

Color Unified Dynamical Axion: model II



arXiv:1805.06465

Color Unified Dynamical Axion: model II



- ➔ Dynamical axion still very heavy
- ➔ Fundamental axion a can be ~ GeV or lower
- ➔ CONS: Large scalar vev ➔ contributes to the EW hierarchy problem

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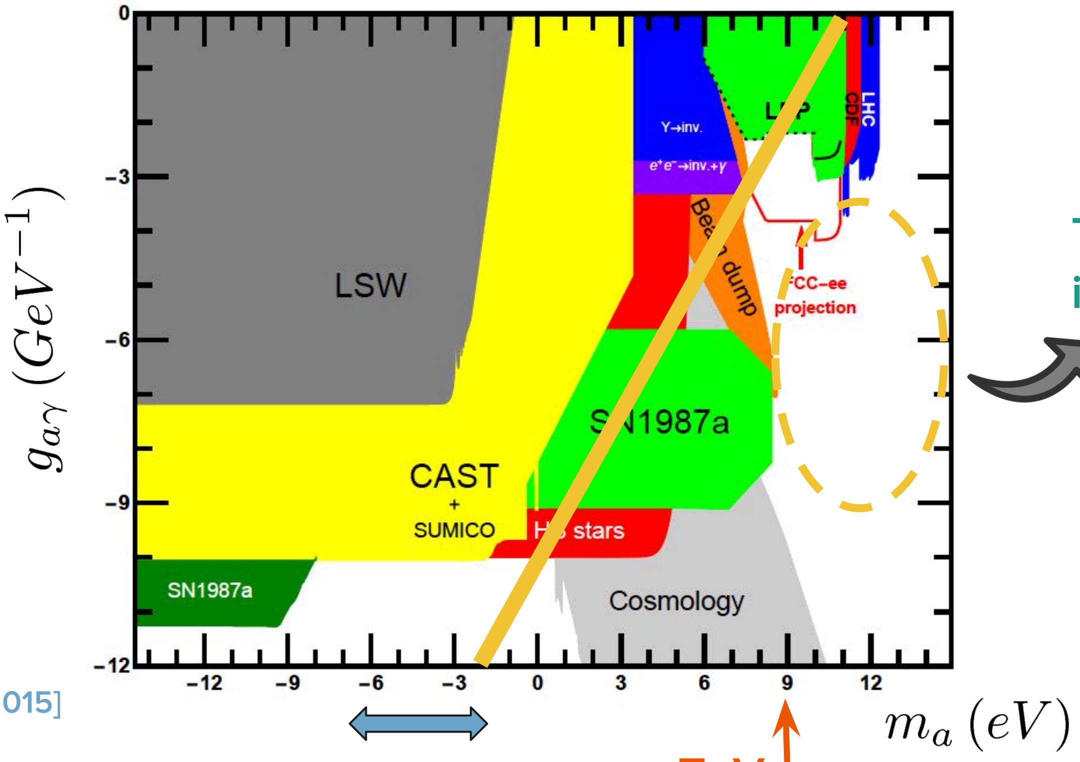
Much territory to explore



True axion region is amplified

[Jaeckel+ Spannowsky 2015]

True QCD region

TeV

arXiv:1805.06465

Conclusions

➔ Strong CP problem solved with massless quarks and unification.

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

➔ Axions are heavy due to Small size instantons

➔ Colored mesons observable at colliders

The $\{m_a, f_a\}$ region that solves the strong CP problem is amplified

arXiv:1805.06465

Thank you!

Color Unified Dynamical Axion: The real thing

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

➔ Spontaneously broken by the vev of Δ

$$\langle \Delta \rangle = \Lambda_{\text{CUT}} \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Allows for a large mass for the tilde sector without spoiling the SM quark masses

$$\kappa_q \, q'_L \Delta^* Q_L \longrightarrow \Lambda_{\text{CUT}} \, \kappa_q \, q'_L \tilde{q}_L$$

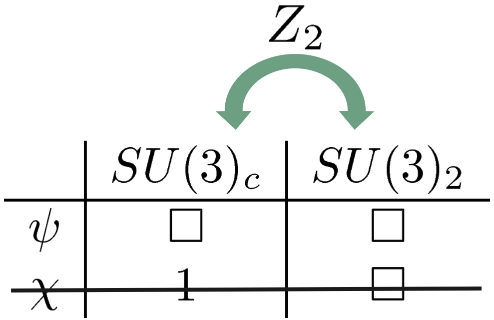
	$SU(6)$	$SU(3')$		$SU(3)_c$	$SU(3)_{\text{diag}}$	$SU(2)_L$	$U(1)_Y$
Q_L	$\square$	1	q_L	$\square$	1	$\square$	$\frac{1}{6}$
			$\mathbf{\tilde{q}_L}$	1	$\square$	$\square$	$\frac{1}{6}$
U^c_L	$\bar{\square}$	1	u^c_L	$\bar{\square}$	1	1	$-\frac{2}{3}$
			$\mathbf{\tilde{u}^c_L}$	1	$\bar{\square}$	1	$-\frac{2}{3}$
D^c_L	$\bar{\square}$	1	d^c_L	$\bar{\square}$	1	1	$\frac{1}{3}$
			$\mathbf{\tilde{d}^c_L}$	1	$\bar{\square}$	1	$\frac{1}{3}$
Ψ_L	20	1	ψ_L	$\square$	$\bar{\square}$	1	0
			ψ^c_L	$\bar{\square}$	$\square$	1	0
			$2 \times \psi_\nu$	1	1	1	1
q'_L	1	$\bar{\square}$	$\mathbf{q'_L}$	1	$\bar{\square}$	$\square$	$-\frac{1}{6}$
u'^c_L	1	$\square$	$\mathbf{u'^c_L}$	1	$\square$	1	$\frac{2}{3}$
d'^c_L	1	$\square$	$\mathbf{d'^c_L}$	1	$\square$	1	$-\frac{1}{3}$
Δ	$\square$	$\bar{\square}$	–	–	–	1	0

arXiv:1805.06465

Alternatives to the dynamical Axion

- ➔ Only one massless quark and a Z_2 [Hook 15]
- ➔ Complete copy of the SM
- ➔ The Z_2 ensures $\theta_2 = \theta_{QCD}$
- ➔ No light axion: $m^2 \sim \frac{\Lambda_2^4}{f_a^2}$
- ➔ The mirror EW sector has a large vev:

$$v_2 \gg v \implies m'_q \gg m_q, \implies \Lambda' \gg \Lambda_{QCD}$$



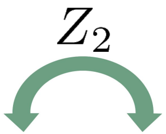
	$SU(3)_c$	$SU(3)_2$
ψ	☐	☐
~~χ~~	~~1~~	~~☐~~

In our work: UNIFICATION

arXiv:1805.06465

SM mirror world axion

[Berezhiani et al, 01]



- SMxSM’ ➔ theta=theta’
- 2HDM + S
- Like Rubakov but without SU(5)
- One shared U(1)PQ:
  - PQWW axion with respect to the mirror world
  - KSVZ axion with respect to SM