New Perspectives on the QCD axion

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Strong CP problem

$$\mathcal{L}_{QCD} \supset \theta G\tilde{G}$$ CP-odd term

Basis independent: $\bar{\theta} = \theta + \arg(\det \mathcal{M}_q)$

Observable effect

Neutron electric dipole moment: $d_N \simeq (5 \times 10^{-16} e \cdot \mathrm{cm})\bar{\theta}$ [Crewther, DiVecchia, Veneziano, Witten,1979]

$$|d_N| \lesssim 3 \times 10^{-26} e \cdot \mathrm{cm} \quad \Rightarrow \quad \boxed{\bar{\theta} \lesssim 10^{-10}}$$

Why is $\bar{\theta}$ so small?

$\bar{\theta}$ does not appear to be "anthropic"

Our Universe possible for $0 \lesssim \bar{\theta} \lesssim 0.1$

[Ubaldi: 0811.1599][DIne, Haskins, Ubaldi, Xu: 1801.03466]
[Lee,Meissner,Olive,Shifman,Vonk: 2006.12321]

Dynamical Solution: PQ mechanism and axion

[Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]

Axion: $\Phi = \frac{1}{\sqrt{2}}(f_a + \rho)e^{i\frac{a}{f_a}}$ $\qquad$ $U(1)_{\rm PQ}$ spontaneously broken $\quad \langle\Phi\rangle = \frac{f_a}{\sqrt{2}}$

$$\Rightarrow \quad \mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \frac{1}{4}a g_{a\gamma\gamma}F\tilde{F} + \frac{1}{f_a}J^\mu\partial_\mu a$$

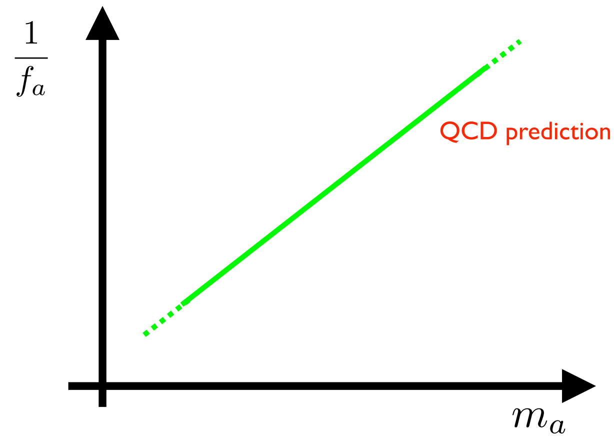
Axion potential: $V_{\rm QCD}(a) \simeq -m_a^2 f_a^2 \cos\left(\frac{a}{f_a} + \bar{\theta}\right) + \ldots$ $\Rightarrow$ *minimum:* $\theta_{\rm eff} \equiv \frac{a}{f_a} + \bar{\theta} = 0$!

solves strong CP problem!

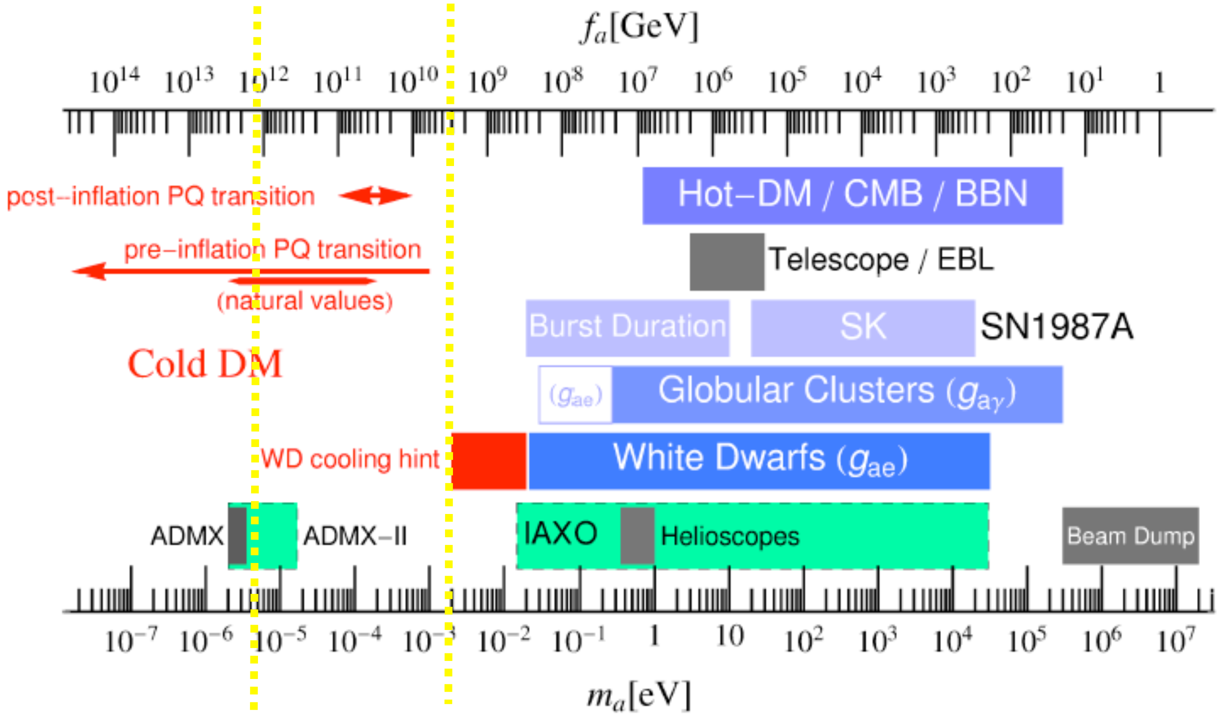
$$\Rightarrow \quad m_a^2 = \frac{\mathcal{T}}{f_a^2} \qquad \mathcal{T} \equiv -i\int d^4x\, \langle 0|\mathrm{T}\left[\frac{1}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}(x),\ \frac{1}{32\pi^2}G^b_{\rho\sigma}\widetilde{G}^{b\rho\sigma}(0)\right]|0\rangle$$

topological susceptibility

$$\Rightarrow \quad m_a^2 f_a^2 \sim m_q \Lambda_{\rm QCD}^3 = \text{constant}$$



QCD axion limits



$$\boxed{10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}}$$

$$\frac{1}{f_a} J^\mu \partial_\mu a \quad \Rightarrow \quad \text{axion weakly-coupled - “invisible”}$$

$$m_a^2 f_a^2 \sim m_q \Lambda_{\rm QCD}^3 \quad \Rightarrow \quad 10^{-5} \text{ eV} \lesssim m_a \lesssim 10^{-3} \text{ eV}$$

Origin of dim-5 axion-gluon coupling?

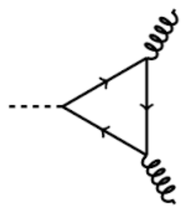
Example: KSVZ [Kim '79; Shifman, Vainshtein, Zakharov '80] (Also DFSZ [Dine, Fischler, Srednicki '81; Zhitnitsky '80])

$U(1)_{PQ}$ Dirac fermion: $\Psi \to e^{iq_\Psi \alpha \gamma_5}\Psi$ complex scalar: $\Phi \to e^{iq_\Phi \alpha}\Phi$

Scalar potential: $V(\Phi) = -m_{PQ}^2|\Phi|^2 + \lambda_{PQ}|\Phi|^4$ ➡ $\langle \Phi \rangle = \frac{f_a}{\sqrt{2}}$ $f_a = \sqrt{\frac{m_{PQ}^2}{\lambda_{PQ}}}$

Yukawa coupling: $(2q_\Psi + q_\Phi = 0)$ $\Delta\mathcal{L} = h_{ij}\Phi\bar{\Psi}_{Ri}\Psi_{Lj} + \mathrm{h.c.}$ ➡ $m_\Psi \sim h\frac{f_a}{\sqrt{2}}$

Integrate out Dirac fermions:



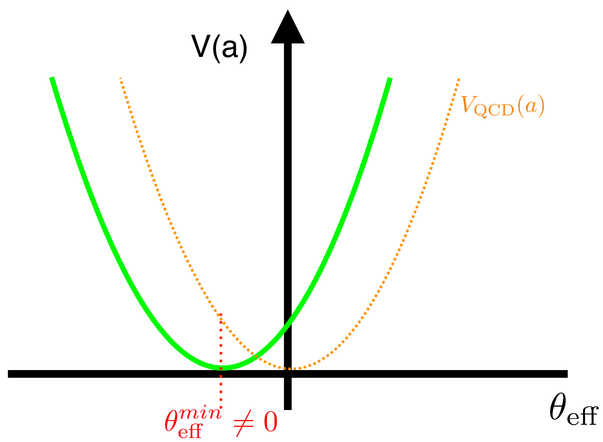
➡ $\frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$

BUT Origin of PQ potential? Why is $m_{PQ} \ll M_P$?

Axion quality:

[Georgi, Hall, Wise 1981; Giddings, Strominger 1988; S.J.Rey 1989; Holman et al 1992; March-Russell, Kamionkowski 1992]

Gravitational violation of $U(1)_{\rm PQ}$ $\quad \dfrac{|c_n|e^{i\delta_n}}{M_P^{n-4}}\Phi^n + h.c.$ $\quad \Rightarrow \quad V(a) = V_{\rm QCD}(a) - \dfrac{|c_n| f_a^n}{M_P^{n-4}}\cos\left(\dfrac{na}{f_a}+\delta_n\right)$



$\Rightarrow$ *minimum:* $\theta_{\rm eff} \neq 0$! $\quad$ axion quality problem

Terms must be suppressed to very high order! $\quad \boxed{n \geq 10} \quad (c_n \sim 1)$

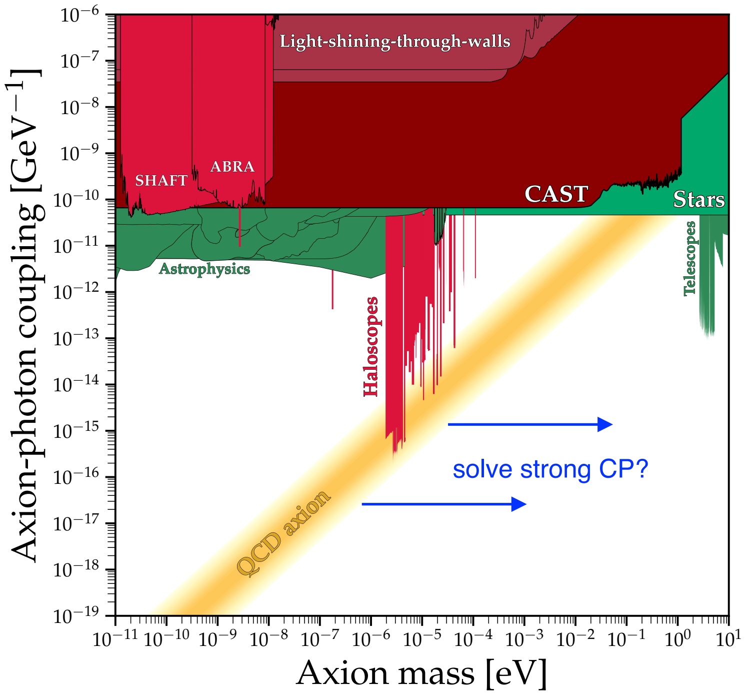
[Note: gravitational instantons $\quad c_n \sim e^{-S} \longrightarrow \quad S \geq 200$ but $S \sim \log \dfrac{M_P}{f_a\sqrt{g_s}} \sim \dfrac{3}{2}\log\dfrac{1}{g_s}$ for dynamical radial mode]

[Alvey, Escudero: 2009.03917]

Questions

- Origin of the PQ breaking potential and spontaneous breaking scale f_a ?
- How to solve the axion quality problem? Connection to GUT or supersymmetry?
- Can the QCD axion mass be different?

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}$$

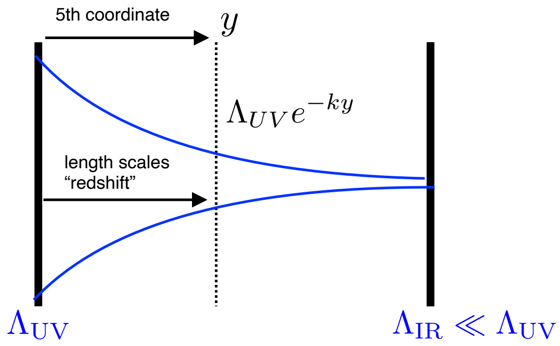


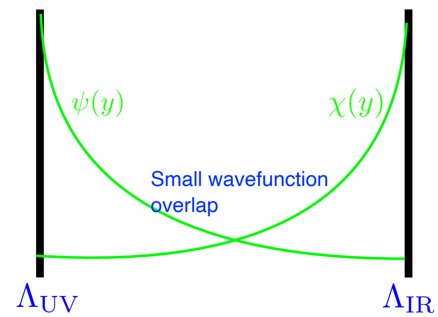
Use 5th dimension to address these questions!

Why use the 5th dimension?

- Can generate a hierarchy of scales and small couplings!

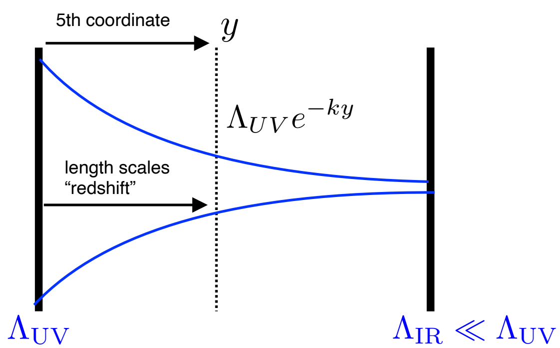
5D AdS

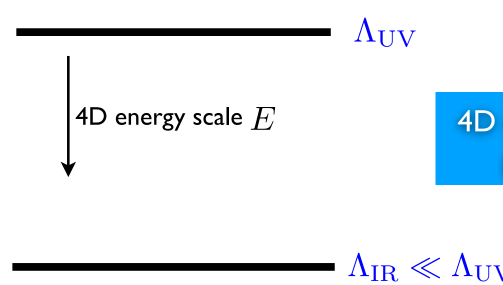




- "Warped" dimension is dual to 4D strong dynamics!

5D AdS





4D strongly-coupled gauge theory

"Holographic view"

I. Axion Quality Problem [Cox, TG, Nguyen 1911.09385]

5D metric: $ds^2 = A^2(z)(dx^2 + dz^2) \equiv g_{MN} dx^M dx^N$ $\quad A(z) = \frac{1}{kz}$

AdS curvature scale

"slice of AdS"

[Randall, Sundrum '99]
[Dienes, Dudas, TG '99]
[Choi '03; Flacke, Gripaios, March-Russell, Maybury '06]

$U(1)_{PQ}$

$\cancel{U(1)_{PQ}}$ $\quad \Phi = \eta(z) e^{ia(x,z)}$ $\quad U(1)_{PQ}$

$\boxed{m_\Phi^2 = \Delta(\Delta - 4)k^2}$

"Bulk mass"

πR

$\Lambda_{\rm UV}$ $\quad \Lambda_{IR} = \Lambda_{UV} e^{-\pi k R}$

Explains PQ scale

PQ symmetry breaking ⇒

$$\boxed{\eta(z) = k^{3/2}\left(\lambda (kz)^{4-\Delta} + \sigma (kz)^{\Delta}\right)}$$

"Bulk VEV"

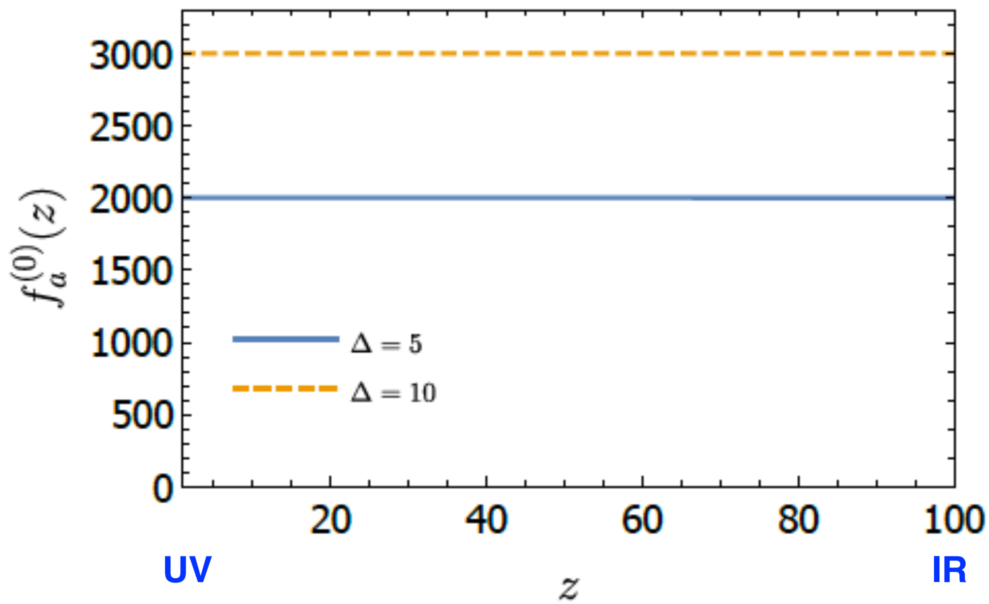
$$\lambda = \frac{\ell_{UV}}{\Delta - 4 + b_{UV}} (k z_{UV})^{\Delta - 4},$$ "explicit" breaking

$$\sigma = \sqrt{v_{IR}^2 - \frac{\Delta}{2\lambda_{IR}}} (k z_{IR})^{-\Delta} \equiv \sigma_0 \, (k z_{IR})^{-\Delta}$$ "spontaneous" breaking

No UV PQ-breaking $(\lambda = 0)$

$(z_{IR} \gg z_{UV})$

$$f_a^{(0)}(z) \simeq \frac{z_{IR}}{\sigma_0}\sqrt{\Delta - 1}\left(1 + \frac{g_5^2 k \sigma_0^2}{4\Delta(\Delta-1)}\left(\frac{(\Delta-1)^2}{2\Delta-1} + \frac{z^2}{z_{IR}^2}\left(\left(\frac{z}{z_{IR}}\right)^{2(\Delta-1)} - \Delta\right)\right) + \mathcal{O}(\sigma_0^4)\right)$$



Global $U(1)_{PQ}$ symmetry: $\boxed{a^{(0)}(x^\mu) \to a^{(0)}(x^\mu) + \alpha_0}$

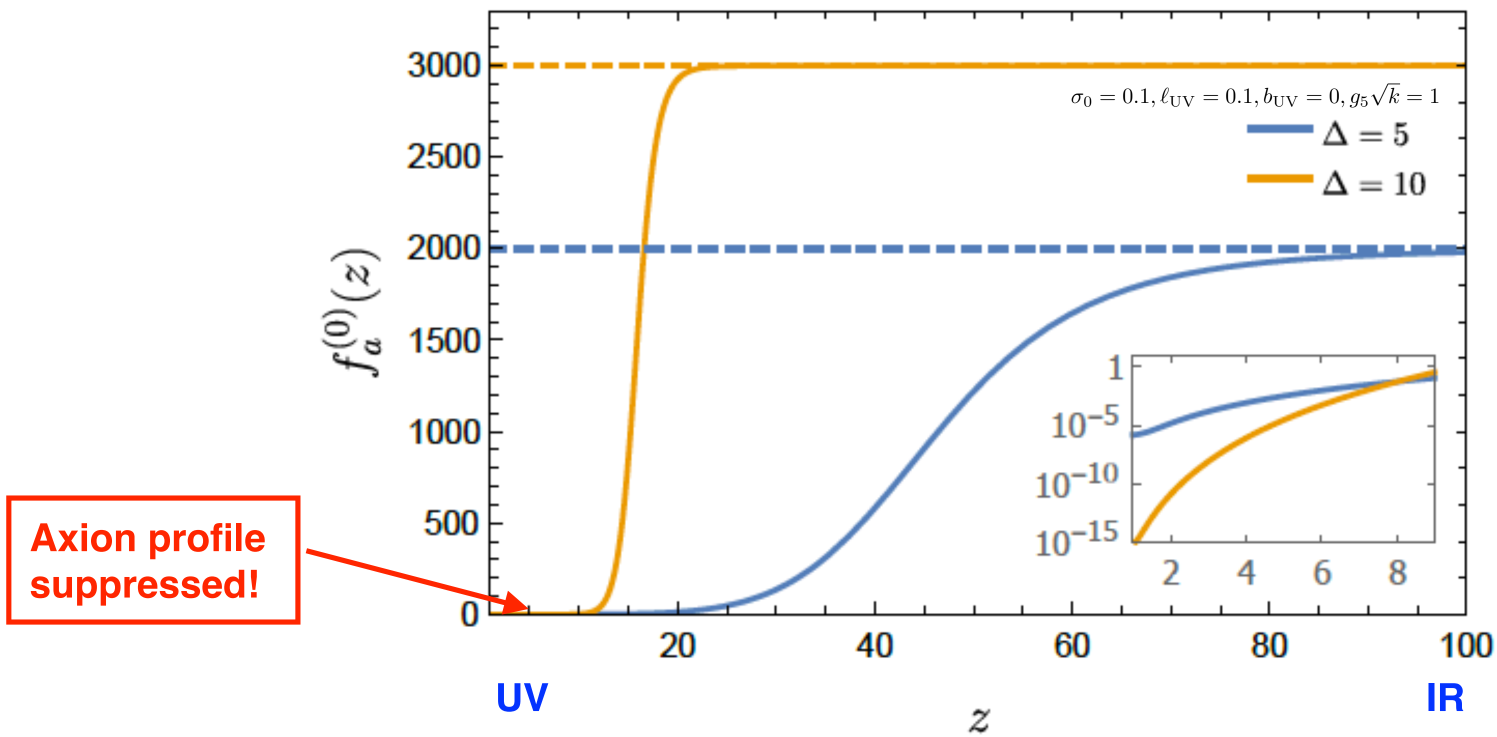
Massless axion

UV PQ-breaking $(\lambda \neq 0)$

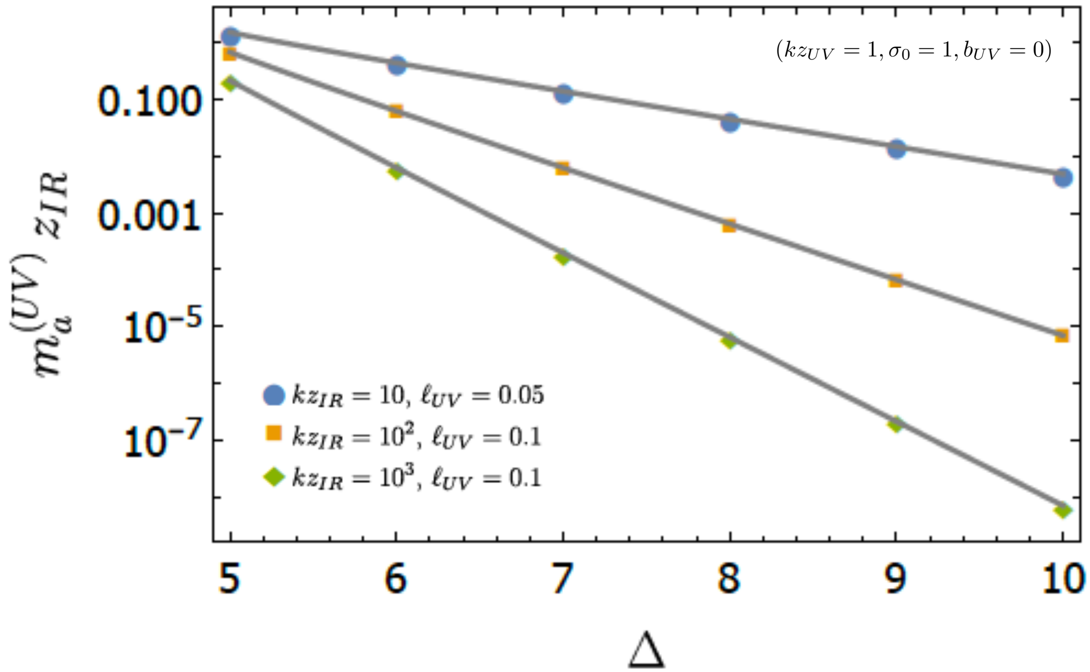
$$U_{UV}(\Phi) \supset -2\ell_{UV} k^{5/2} \eta \cos(a) = -2\ell_{UV} k^{5/2} \eta \left(1 - \frac{1}{2}a^2 + \dots\right)$$

$(z_{IR} \gg z_{UV})$

$$f_a^{(0)}(z) \simeq z_{IR} \frac{k^{3/2}}{\eta(z)} \sqrt{\Delta - 1} \left(\frac{z}{z_{IR}}\right)^{\Delta} \left[1 + \frac{2\lambda(\Delta-2)(kz_{UV})^{\Delta}(kz)^{2(2-\Delta)}}{\ell_{UV} + 2\sigma_0(\Delta-2)(z_{UV}/z_{IR})^{\Delta}}\right]$$



UV axion mass $(\lambda \neq 0)$



UV axion mass *suppressed* for large Δ

Bulk Chern-Simons term: $-\dfrac{\kappa}{32\pi^2}\displaystyle\int_{z_{UV}}^{z_{IR}} d^5x\, \epsilon^{MNPQR} V_M G^a_{NP} G^a_{QR}$ generates axion-gluon coupling

$$(m_a^{(UV)})^2 = \frac{4\ell_{UV}\sigma_0(\Delta-2)}{\kappa^2(\Delta-4+b_{UV})}\left(\frac{\kappa\sqrt{\Delta-1}}{\sigma_0}\right)^{\Delta}\left(\frac{F_a}{\Lambda_{UV}}\right)^{\Delta-4} F_a^2$$

where

$$F_a \simeq \frac{1}{\kappa}\frac{\sigma_0}{\sqrt{\Delta-1}} z_{IR}^{-1}$$

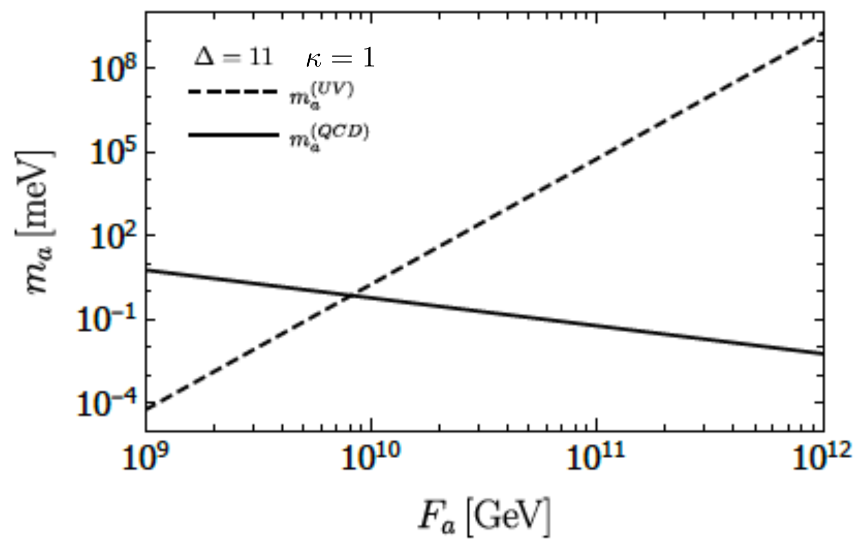
Axion potential:

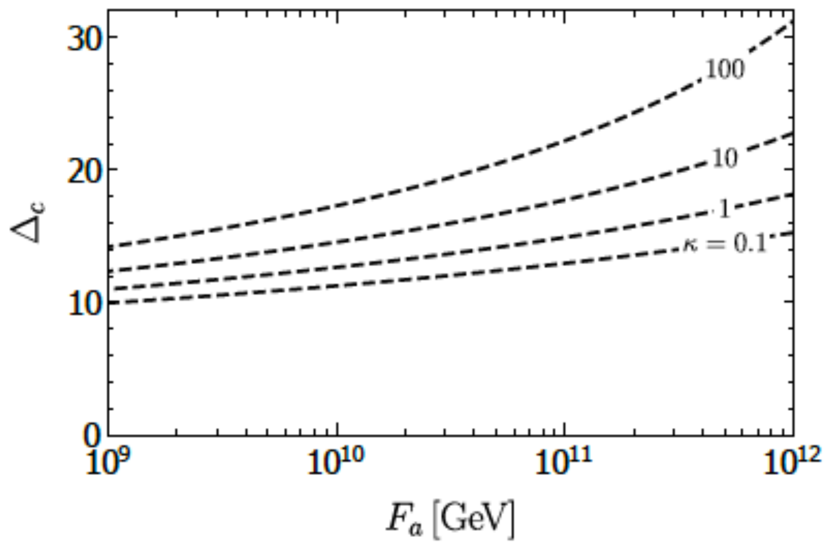
UV explicit PQ violation

$$V(a^{(0)}) \simeq -(m_a^{(QCD)})^2 F_a^2 \cos\left(\frac{a^{(0)}}{F_a} + \bar{\theta}\right) - \boxed{(m_a^{(UV)})^2} F_a^2 \cos\left(\frac{a^{(0)}}{F_a} + \delta\right)$$

relative phase

Require: $(m_a^{(UV)})^2 \lesssim 10^{-10}\,(m_a^{(QCD)})^2$





$$10^9 \text{ GeV} \lesssim F_a \lesssim 10^{12} \text{ GeV} \quad \Rightarrow \quad \Delta_c \gtrsim 10$$

Solves axion-quality problem!

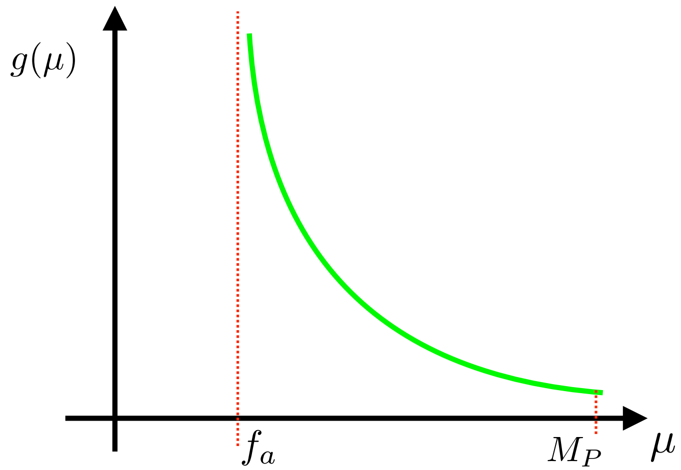
AdS/CFT dictionary

5D		4D
local $U(1)_{PQ}$ symmetry	$\leftrightarrow$	global $U(1)_{PQ}$ symmetry
$\Phi,\ m_\Phi^2 = \Delta(\Delta-4)k^2$	$\leftrightarrow$	$\mathcal{O}$, dimension Δ
$\Lambda_{\rm UV} e^{-\pi k R} = \Lambda_{\rm IR}$	$\leftrightarrow$	$\Lambda_{\rm IR} = \Lambda_{\rm UV} e^{-\frac{8\pi^2}{b_{\rm CFT} g^2}}$
σ	$\leftrightarrow$	$\langle \mathcal{O} \rangle$
λ	$\leftrightarrow$	$\lambda \phi_0 \mathcal{O}$

Holographic interpretation:

5D axion,
local U(1) PQ symmetry
$\Leftrightarrow$
4D composite axion, accidental
global U(1) PQ symmetry

Composite Axion: [Kim 1985; Choi, Kim 1985];



$f_a \ll M_p$

No need to tune mass parameters in KSVZ potential (or DFSZ) potential!

Axion quality:

$$\frac{|c_n| e^{i\delta_n}}{M_P^{n-4}} \Phi^n \quad (n \gtrsim 10) \qquad \longleftrightarrow \qquad \frac{c_\Delta}{M_P^{\Delta-4}} \mathcal{O} \sim \frac{c_\Delta}{M_P^{\Delta-4}} (\underbrace{\psi_i \psi_j \ldots\ldots \psi_k}_{\text{due to gauge + Lorentz symmetry!}}) \quad (\Delta \gtrsim 10)$$

Examples: [Randall1992];[Cheng, Kaplan 2001];[Redi, Sato 2016];[Lillard, Tait 2018];[Contino,Podo, Revello: 2112.09635]

Build models which better incorporate SM features:

- Gives rise to QCD axion
- SM part of strong dynamics
- Connection to GUT physics? ← Will give an example

I. High-quality composite Pati-Salam axion

[TG, Murayama, Quilez: 2505.08866]

strong dynamics: $SU(N_c) \qquad 10 \times Q(\Box) \qquad 10 \times P(\bar{\Box})$

flavor symmetry: $SU(10)_L \times SU(10)_R$

$\cup \qquad \cup$

"weakly" gauged: $SO(6) \times SO(4) \qquad Sp(10)$

⇨ P, Q fermions are naturally massless!

	$G_{\rm local}$				$G_{\rm global}$	
	$SU(N_c)$	$Sp(10)$	$SO(6)$	$SO(4)$	$U(1)_B$	$U(1)_{PQ}$
Q_6	$\mathbf{N_c}$	**1**	**6**	**1**	$+1$	$+2$
Q_4	$\mathbf{N_c}$	**1**	**1**	**4**	$+1$	-3
P	$\bar{\mathbf{N}}_c$	**10**	**1**	**1**	-1	**0**

Symmetry breaking: $\langle P^r Q_s \rangle = \Lambda^3 \delta^r_s$ (r,s = flavor index)

$$SO(6) \times SO(4) \times Sp(10) \to SU(3) \times U(1)_{B-L} \times SU(2)_L \times U(1)_{I_{3R}}$$

Nambu-Goldstone bosons:

$$\dim[SU(10)_L \times SU(10)_R / SU(10)_V] = 99 \quad \text{NGBs}$$

$$\dim[SO(6) \times SO(4) \times Sp(10)/U(3) \times U(2)] = 63 \quad \text{NGBs eaten}$$

$$36 \quad \text{NGBs remaining}$$

Under $U(3) \times U(2)$ $\qquad (\mathbf{8_0}, \mathbf{1_0}) \oplus (\mathbf{1_0}, \mathbf{3_0}) \oplus (\mathbf{3_1} + \bar{\mathbf{3}}_{-1}, \mathbf{2_1} + \mathbf{2_{-1}}) \oplus (\mathbf{1_0}, \mathbf{1_0})$

Obtain mass $\sim g^2 \Lambda^2$ QCD axion!

PQ-violating operators

Need SO(6) (SO(4)), Sp(10) gauge invariants:

$$e.g. \qquad (Q_6^2)^{\overbrace{\{a,b\}}^{\text{SU(Nc) symmetric}}} \equiv \underbrace{\delta^{ij}}_{SO(6)}(Q^a_{6i\alpha}\epsilon^{\alpha\beta}Q^b_{6j\beta}) \qquad\qquad (Q_6^2)^{[a,b]}_{\mu\nu} \equiv \delta^{ij}(Q^a_{6i\alpha}\sigma^{\alpha\beta}_{\mu\nu}Q^b_{6j\beta})$$

$$(P^2)_{\underbrace{[a,b]}_{\text{SU(Nc) antisymmetric}}} \equiv \overbrace{J_{rs}}^{Sp(10)}(P^{r\alpha}_a\epsilon_{\alpha\beta}P^{s\beta}_b) \qquad\qquad (P^2)^{\mu\nu}_{\{a,b\}} \equiv J_{rs}(P^{r\alpha}_{\{a}\sigma^{\mu\nu}_{\alpha\beta}P^{s\beta}_{b\}})$$

$SU(N_c)$ invariants ⇨ no. P fermions = no. Q fermions

⇨ mass terms and four-fermion operators (QQPP) are forbidden!

⇨ obtain (QQPP)(QQPP) ⟵ eight-fermion operators!

$$e.g. \qquad \mathcal{O}_{12} \equiv \frac{1}{M_P^8}(Q^2_{4,6})^{\{a,b\}}(Q^2_{4,6})^{[c,d]}_{\mu\nu}(P^2)_{[c,d]}(P^2)^{\mu\nu}_{\{a,b\}}$$ ⟵ dimension 12

$$\frac{1}{M_P^8}\mathcal{O}_{12} \sim \frac{f_a^{12}}{M_P^8}e^{i\frac{8a}{f_a}} \quad ⇨ \quad V(a) \supset f_a^4\left(\frac{f_a}{M_P}\right)^8 \cos\theta_{eff}$$ (like warped model with $\Delta = 12$!)

Dark matter

(i) Pre-inflation

Dark matter via misalignment provided $10^{10}\text{GeV} \lesssim f_a \lesssim 10^{12}\text{GeV}$

$\frac{1}{M_P^8}\mathcal{O}_{12}$ ➡ $\theta_{eff} \lesssim 10^{-10}$ for $f_a \lesssim 10^{11}$ GeV

⟶ although $H_I \lesssim 10^{-5} f_a \sim 10^6$ GeV to suppress isocurvature perturbations

(ii) Post-inflation

Axion potential: $U(1)_{PQ} \to \mathbb{Z}_{4N_c}$

$\mathcal{O}_{12}$ explicitly breaks $\mathbb{Z}_{4N_c}$ discrete symmetry

⟶ provides bias potential $\frac{1}{M_{PQ}^8}\mathcal{O}_{12}$ ⟵ causes domain wall/string decay

⟶ dark matter abundance provided $f_a \sim 10^9$ GeV$, \delta = 10^{-2}, M_{PQ} = 10^{15-17}$ GeV [Kawasaki,Saikawa,Sekiguchi: 1412.0789]

Axion-photon coupling

$U(1)_{\rm EM} \supset SO(6) \times SO(4) \times Sp(10)$ ➡ P, Q electromagnetic charges fixed!

$$\boxed{\frac{E}{N} = -\frac{7}{3}}$$ ➡ $$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\left(-\frac{7}{3} - 1.92(4)\right)$$

Bonus feature

Grand Unification

$$\underbrace{SO(6) \times SO(4)}_{SU(4) \times SU(2)_L \times SU(2)_R} \rightarrow SO(10)$$

Pati-Salam!

SM: $3 \times (4,2,1)$ Q, L

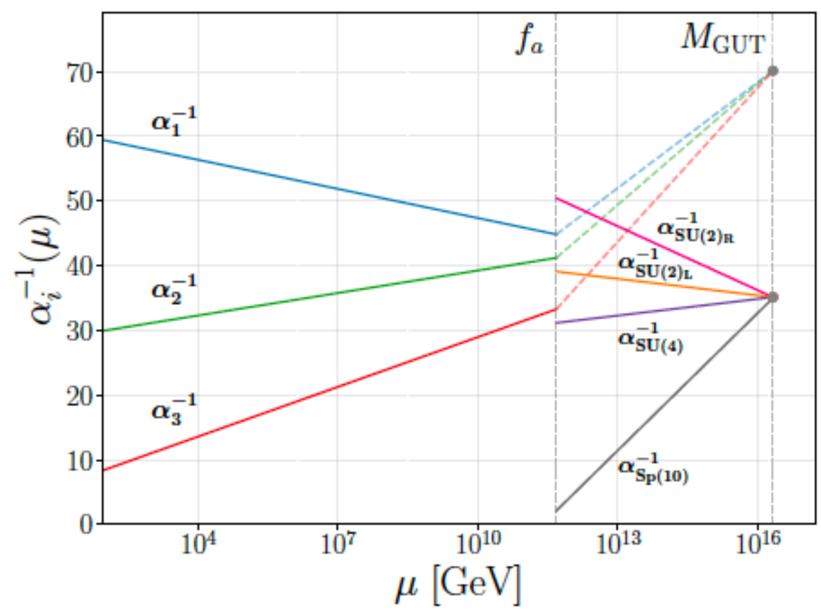
$3 \times (\bar{4},2,1)$ $\bar{u}, \bar{d}, \bar{e}, N$

$(1,2,2) \subset \mathbf{10}$ Higgs

$\Phi = (10,1,3) \subset \mathbf{126}$ to break $U(1)_{B-L} \times U(1)_{I_3}$

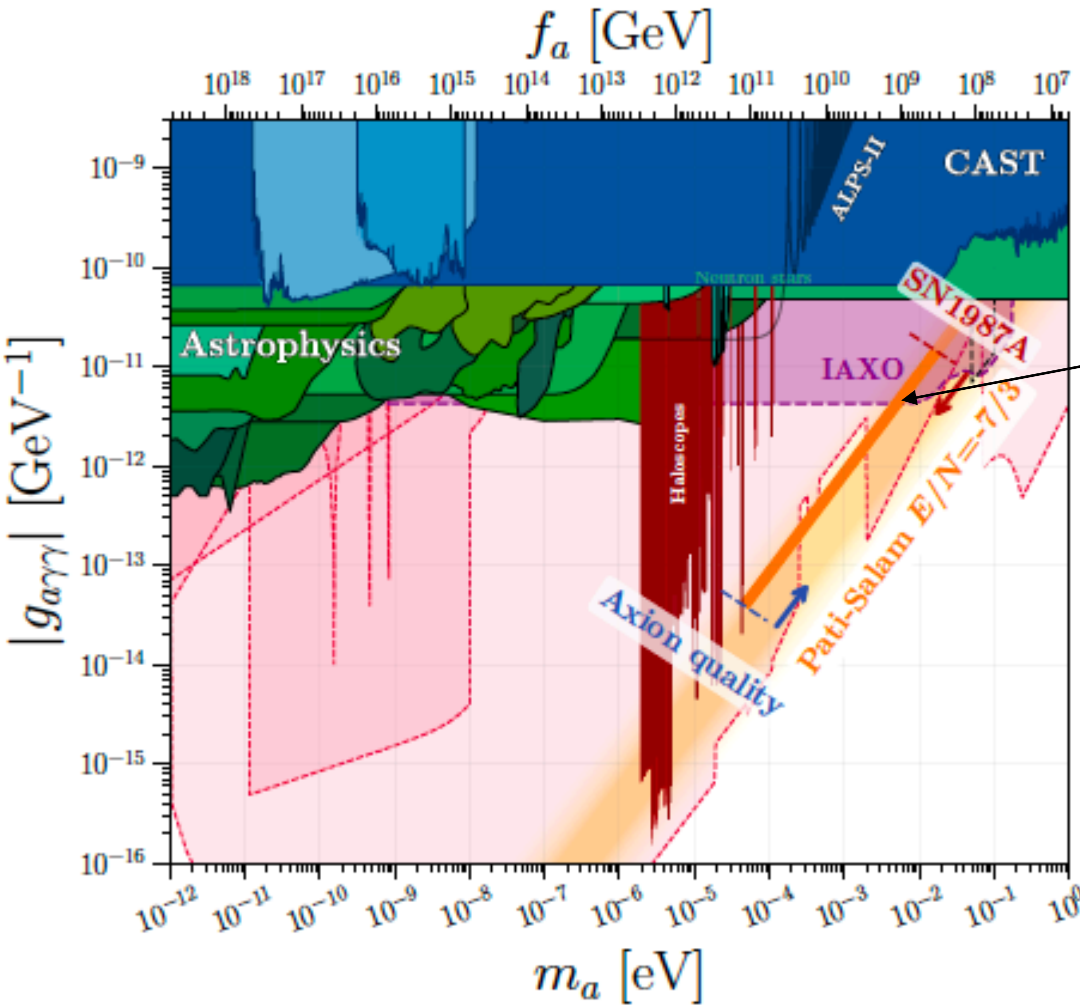
→ dimension 8 PQ-violating op. $\Phi^\dagger \Phi QQPP$

→ forbidden by anomaly-free $\mathbb{Z}_8$ symmetry!



Axion-photon coupling limits on Pati-Salam axion

[TG, Murayama, Quilez: 2505.08866]



Might be seen at IAXO (CERN)!

ALSO: High-quality axion from SUSY chiral dynamics [TG, Murayama, Noether, Quilez: 2508.21813] [see also Sato, Takeshita: 2508.21820]

2. Axion mass from 5D small instantons

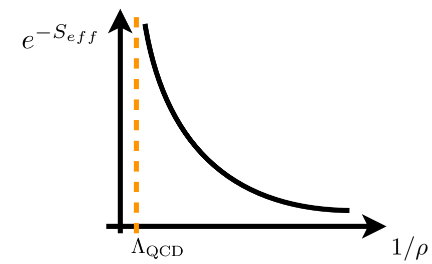
QCD axion mass:

$$m_a^2 = \frac{\mathcal{T}}{f_a^2} \qquad \mathcal{T} \equiv -i \int d^4x\, \langle 0 | \mathrm{T} \left[\frac{1}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}(x),\ \frac{1}{32\pi^2} G^b_{\rho\sigma} \widetilde{G}^{b\rho\sigma}(0) \right] |0\rangle$$

"topological susceptibility"

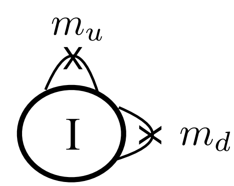
Dilute instanton gas approximation:

$$\mathcal{T} \propto \int \frac{d\rho}{\rho^5} C[3] \left(\frac{2\pi}{\alpha_s(1/\rho)} \right)^6 e^{-\frac{2\pi}{\alpha_s(1/\rho)}}$$



QCD asymptotically free $\qquad \Rightarrow \qquad \mathcal{T} \propto \Lambda_{QCD}^4$

Fermion zero modes: $\quad (\rho m_f)^{N_f} \longrightarrow$ suppression $\dfrac{\prod_f m_f}{\Lambda_{QCD}^{N_f}}$

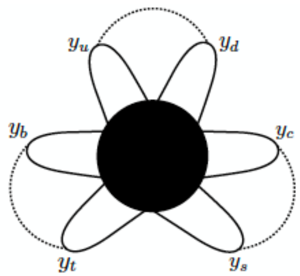


$$\Rightarrow \quad \boxed{m^2_{a,QCD} = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}}$$

How to enhance QCD axion mass?

- Change QCD coupling in UV $\alpha_s(1/\rho) \sim 1$ "Small instantons" $\rho \sim 1/\Lambda_{UV}$

- Close fermion loops with Higgs boson



$$\kappa_f = \frac{y_u}{4\pi}\frac{y_d}{4\pi}\frac{y_c}{4\pi}\frac{y_s}{4\pi}\frac{y_t}{4\pi}\frac{y_b}{4\pi} \approx 10^{-23}$$

$\left(\text{otherwise } \frac{m_u m_d m_c m_s m_b m_t}{\Lambda_{UV}^6}\right)$

$$\Rightarrow \quad \boxed{m_a^2 f_a^2 \sim m_q \Lambda_{\rm QCD}^3 + \Lambda_I^4}$$

new contribution

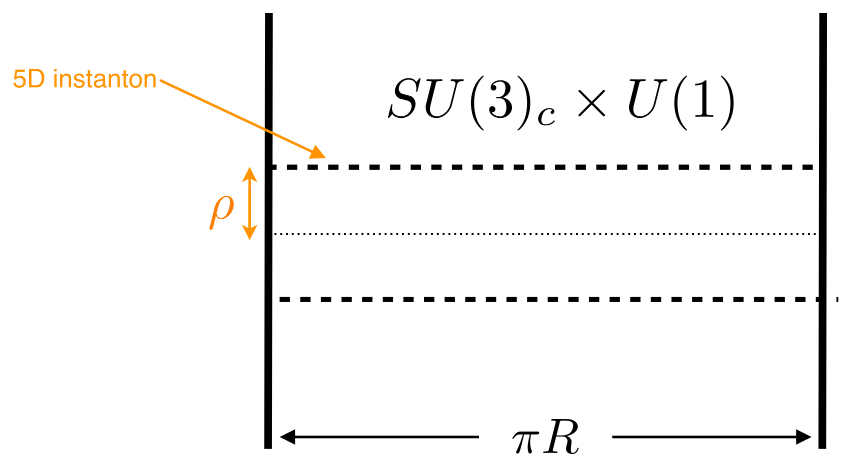
where $\Lambda_I \gg \Lambda_{\rm QCD}$

Use 5th dimension to make QCD axion heavy!

QCD in 5D

Flat space 5D metric: $ds^2 = dx^2 + dy^2$

$$S_5 = -\int d^4x \int_0^L dy \left(\frac{1}{4g_5^2} \mathrm{Tr}[G_{MN}^2] + \frac{b_{CS}}{32\pi^2} \varepsilon^{MNRST} B_M \mathrm{Tr}[G_{NR} G_{ST}] + \frac{1}{4g_5^2} F_{MN}^2 + \dots \right),$$



$A_\mu^{(0)}(x)$ QCD gluon

$B_5^{(0)}(x) \equiv a(x)$ QCD axion

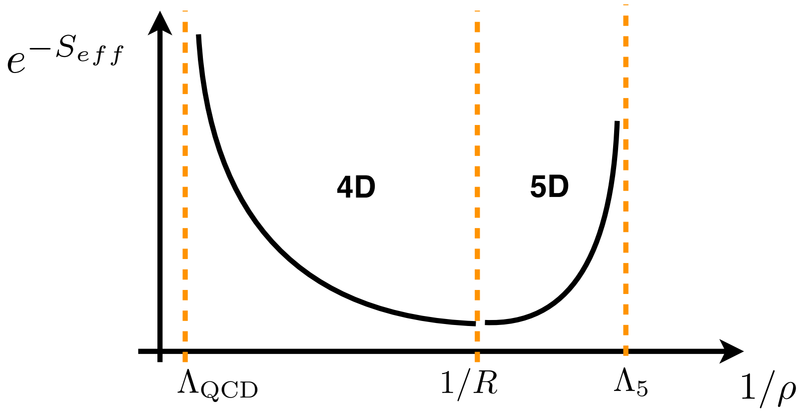
5D instanton: $A_\mu^a(x,y) = A_\mu^{(I)a}(x) = \frac{2\eta_{a\mu\nu}(x-x_0)_\nu}{(x-x_0)^2+\rho^2}, \quad A_5^a(x,y) = 0$

$$\Rightarrow \quad S_5^{(I)} = \frac{8\pi^3 R}{g_5^2} = \frac{2\pi}{\alpha_s}$$

Finite action

5D small instantons [Poppitz, Shirman '02] [TG, Khoze, Pomarol, Shirman: 2001.05610]

Fluctuations + Kaluza-Klein contributions



small instantons!

$$\mathcal{T} \sim \int_{1/\Lambda_5}^{R} \frac{d\rho}{\rho^5} C[3] \left(\frac{2\pi}{\alpha_s(1/R)}\right)^6 e^{-S_{\rm eff}} \equiv \frac{K}{R^4} \propto m_a^2 f_a^2$$

$$S_{\rm eff} = \frac{2\pi}{\alpha_s(1/R)} - 3\xi(R/\rho)\frac{R}{\rho} + b_0 \ln\frac{R}{\rho}$$

power law term!

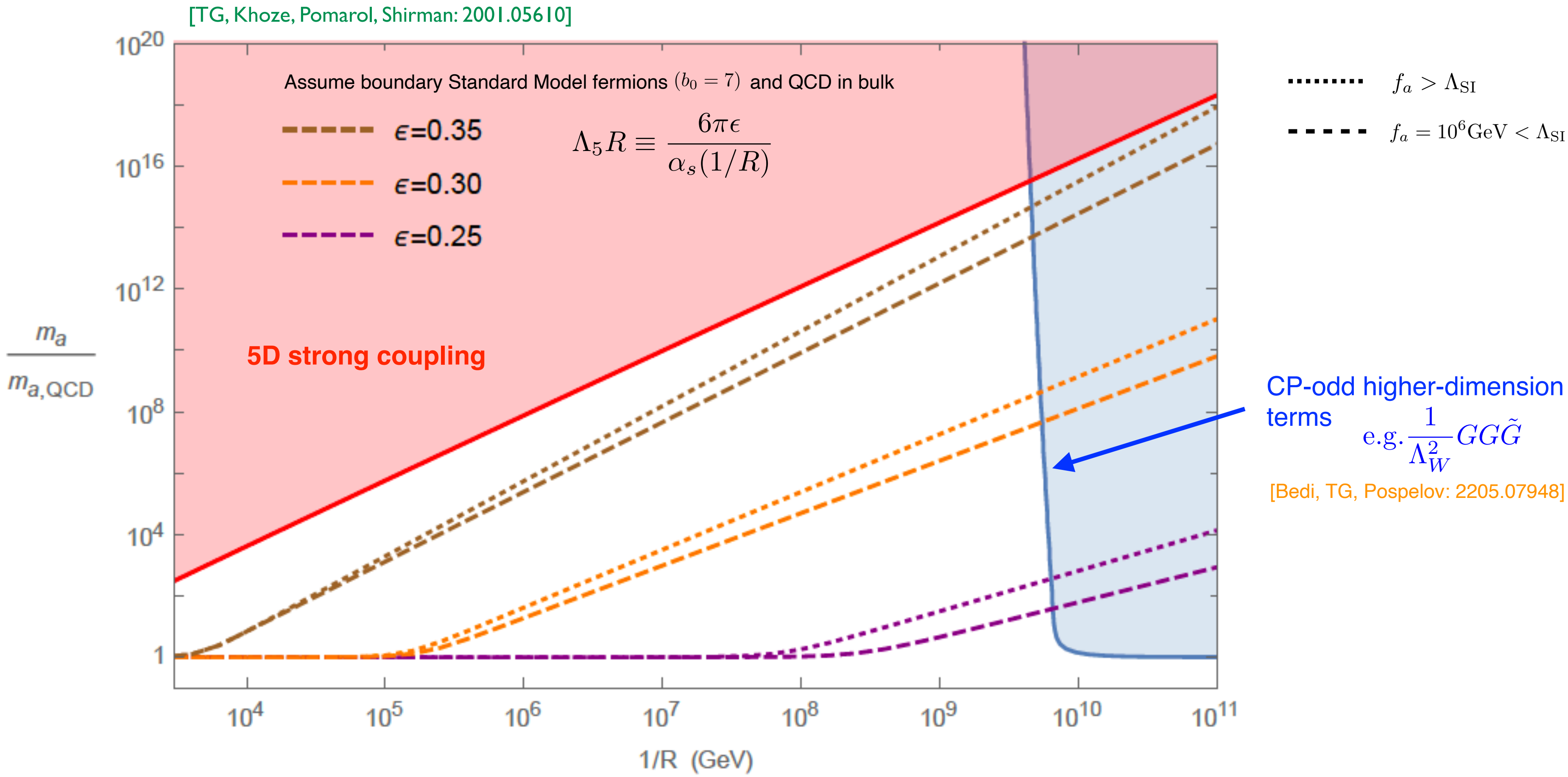
$\xi(R/\rho) \sim 1/3$

$R/\rho \gtrsim 20$

$$K \simeq C[3] \left(\frac{2\pi}{\alpha_s(1/R)}\right)^6 (\Lambda_5 R)^{3-b_0} e^{-\frac{2\pi}{\alpha_s(1/R)} + \Lambda_5 R}$$

power law contribution can overcome suppression

$$\text{Valid up to} \quad \frac{g_5^2 \Lambda_5}{24\pi^3} \sim 1 \quad \text{or} \quad \Lambda_5 R \lesssim \frac{6\pi}{\alpha_s}$$



Small 5D instantons can dominate for $\frac{1}{R} \gtrsim 100 \ \text{TeV}$

Enhanced EDMs [Bedi, TG, Pospelov: 2205.07948]

Higher-dimension CP-odd sources are enhanced by small instantons

Weinberg operator: $\mathcal{L} \supset \frac{1}{\Lambda_W^2} G G \widetilde{G}$

[Also fermion operator: $\mathcal{L} \supset \sum_{ijkl} \frac{\lambda_{ijkl}}{\Lambda_F^2} \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$ [see also Bedi,TG,Grojean,Guedes, Kley,Vuong: 2402.09361]]

$\Rightarrow$ $$V(a) = \chi_W(0) \left(\frac{a}{f_a}\right) + \frac{1}{2}\chi(0)\left(\frac{a}{f_a}\right)^2$$

where $$\chi_W(0) = -i \lim_{k \to 0} \int d^4x\, e^{ikx} \left\langle 0 \left| T \left\{ \frac{1}{32\pi^2} G\widetilde{G}(x), \frac{1}{\Lambda_W^2} G G \widetilde{G}(0) \right\} \right| 0 \right\rangle$$

$\Rightarrow$ $$\boxed{\left\langle \frac{a}{f_a} \right\rangle \equiv \theta_{\rm ind} = -\frac{\chi_W(0)}{\chi(0)} \propto \frac{\Lambda_{\rm SI}^2}{\Lambda_W^2}}$$ $\leftarrow$ Enhanced by $\frac{\Lambda_{\rm SI}}{\Lambda_{\rm QCD}}$

Neutron EDM: $|\theta_{\rm ind}| \lesssim 10^{-10}$ $\Rightarrow$ $$\boxed{\frac{\Lambda_{\rm SI}}{\Lambda_W} \lesssim 10^{-6}}$$

Questions/Future Work

- Incorporate neutrino sector?
  — e.g. right handed neutrinos at $f_a \sim 10^{12}$ GeV [Cox,TG, Paul: 2310.08557]

- Explore other possible strong dynamics
  — completely break GUT group by strong dynamics?

- Study SU(N)/Sp(2N) phase transition in early Universe
  — 1st order phase transition for gravitational wave signal?

- Small instantons in weakly-gauged holographic models

  [TG, Pomarol: 2110.01762]
  $$A^a_\mu(x,z) = 2\eta^a_{\mu\nu}\frac{x_\nu}{x^2}\frac{(x^2+z^2)^2}{x^2\rho^2+(x^2+z^2)^2}$$
  — other solutions that give axion mass enhancement?

- ……..

Summary

QCD axion elegantly solves the strong CP problem, but

- Origin of U(1) and axion decay constant?
  — *naturally explained by new strong dynamics*
  — *can be part of GUT or supersymmetry breaking*
- Axion quality problem?
  — *Avoided by gauge/discrete symmetries which are part of axion strong dynamics*
- Phenomenology
  — *gravitational wave signal from confining phase transition?*
  — *possible colored states near the TeV scale*
- 5D small instantons
  — *can enhance axion mass and not spoil strong CP solution*

Axion properties naturally emerge from strong dynamics!