

New 5D perspectives on the QCD axion

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IAS seminar,
Seoul, South Korea,
February 8, 2023

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 $d_N \simeq (5 \times 10^{-16} e \cdot \text{cm}) \bar{\theta}$

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

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

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

Our Universe possible for $0 \lesssim \bar{\theta} \lesssim 0.1$ [Lee, Meissner, Olive, Shifman, Vink: 2006.12321]

Dynamical Solution: PQ mechanism and axion

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

Axion Lagrangian: $\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \underbrace{\frac{a}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G}}_{\text{dim 5 term}} + \frac{1}{4} a \underbrace{g_{a\gamma\gamma} F\tilde{F}}_{\text{diphoton coupling}} + \frac{1}{f_a} J^\mu \underbrace{\partial_\mu a}_{\text{axial current coupling}}$

Axion mass: $m_a^2 = \frac{\mathcal{T}}{f_a^2}$ $\mathcal{T} \equiv -i \int d^4x \langle 0 | T \left[\frac{1}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}(x), \frac{1}{32\pi^2} G_{\rho\sigma}^b \tilde{G}^{b\rho\sigma}(0) \right] | 0 \rangle$ topological susceptibility

 $m_a^2 f_a^2 \sim \underbrace{\frac{1}{8} \Lambda_{\text{QCD}}^4}_{\text{light-quark contribution}}$ [or precisely, $m_a = 5.70(7) \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$]
[Cortona, Hardy, Pardy Vega, Villadoro, 1511.02867]

Axion quality: Gravitational violation of U(1)_{PQ} $\frac{c_n}{M_P^{n-4}} \Phi^n + h.c.$

Terms must be suppressed to very high order! ($c_n \sim 1, n \geq 10$)

[however, if only gravitational instantons $c_n \sim e^{-S} \rightarrow S \geq 200$]

Where does dim-5 axion coupling come from?

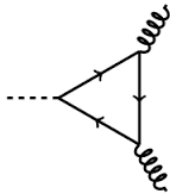
Example: KSVZ [Kim '79; Shifman, Vainshtein, Zakharov '80]

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

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

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

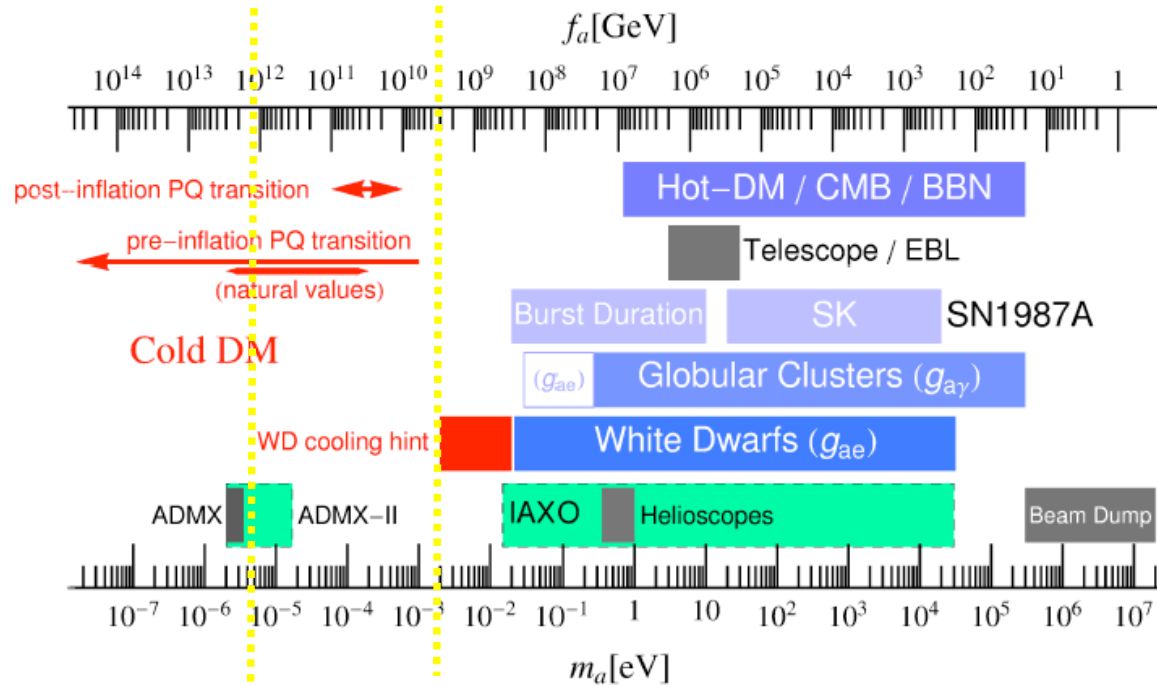
Integrate out
Dirac fermions:



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

(Also DFSZ [Dine, Fischler, Srednicki '81; Zhitnitsky '80])

QCD axion limits



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

$$\frac{1}{f_a} J^\mu \partial_\mu a$$



axion weakly-coupled - “invisible”

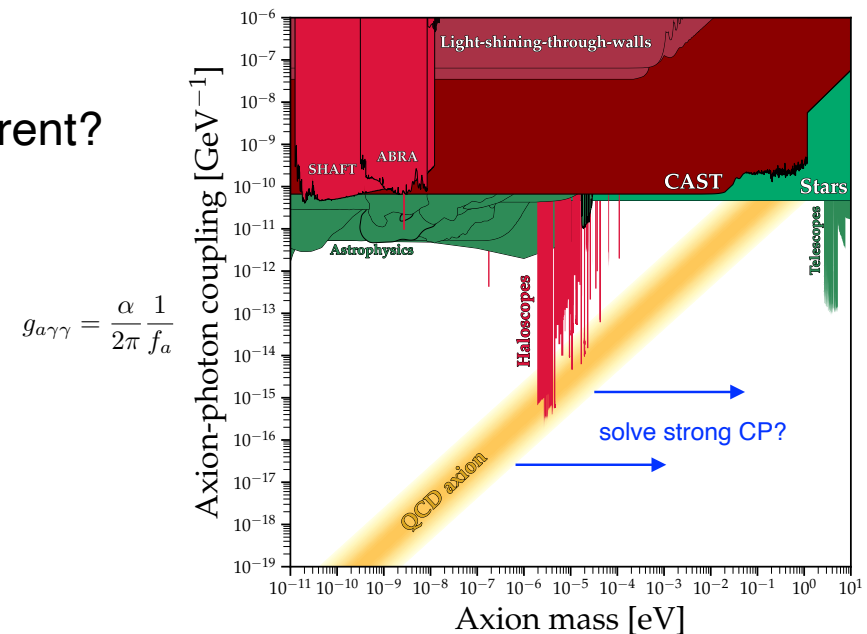
$$m_a^2 f_a^2 \sim \frac{1}{8} \Lambda_{\text{QCD}}^4$$



$$10^{-5} \text{ eV} \lesssim m_a \lesssim 10^{-3} \text{ eV}$$

Questions

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



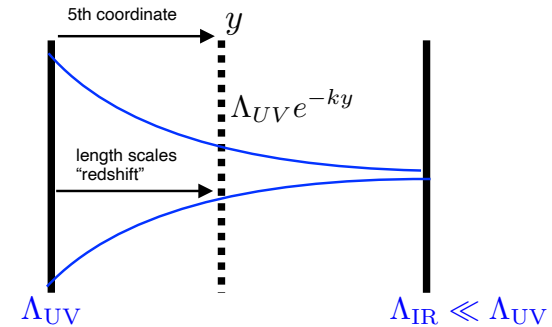
➡ Use 5th dimension to address these questions!

Why use the 5th dimension?

- ◆ Can generate a hierarchy of scales!



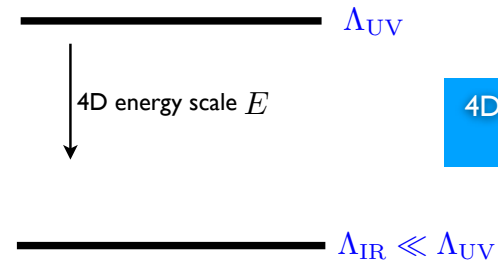
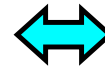
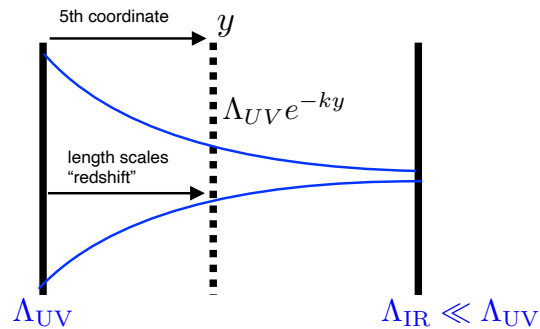
5D AdS



- ◆ “Warped” dimension is dual to 4D strong dynamics!

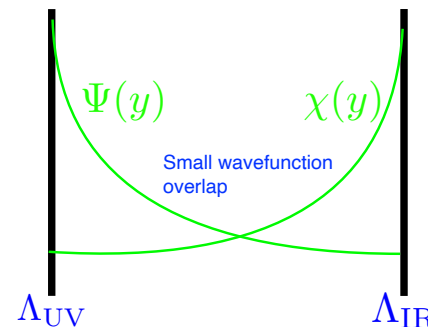


5D AdS



4D strongly-coupled
gauge theory

- ◆ Can generate small couplings!



I. Axion Quality Problem

[Cox, TG, Nguyen 1911.09385]

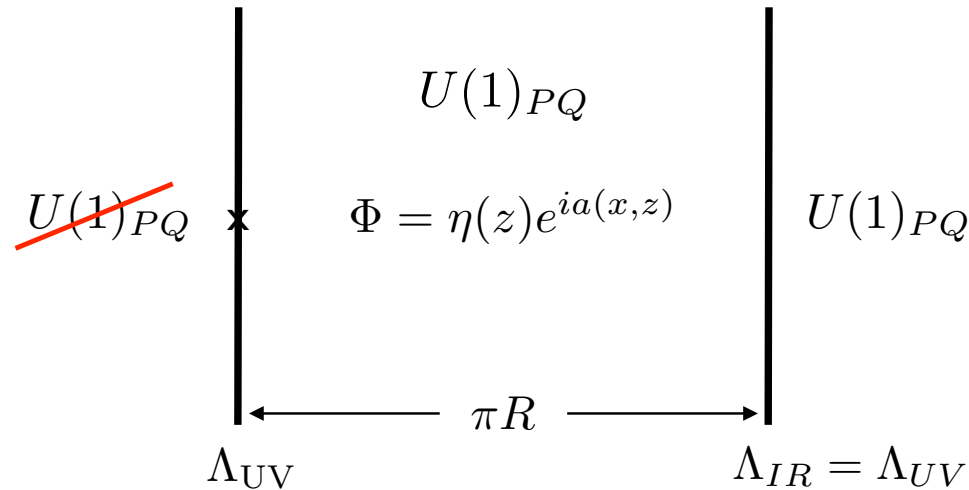
5D metric:

$$ds^2 = A^2(z)(dx^2 + dz^2) \equiv g_{MN}dx^M dx^N$$

$$A(z) = \frac{1}{kz}$$

AdS curvature scale

“slice of AdS”



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

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

“Bulk mass”

Explains
PQ scale

PQ symmetry
breaking



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

“Bulk VEV”

$$\lambda = \frac{\ell_{UV}}{\Delta - 4 + b_{UV}}(kz_{UV})^{\Delta-4},$$

“explicit” breaking

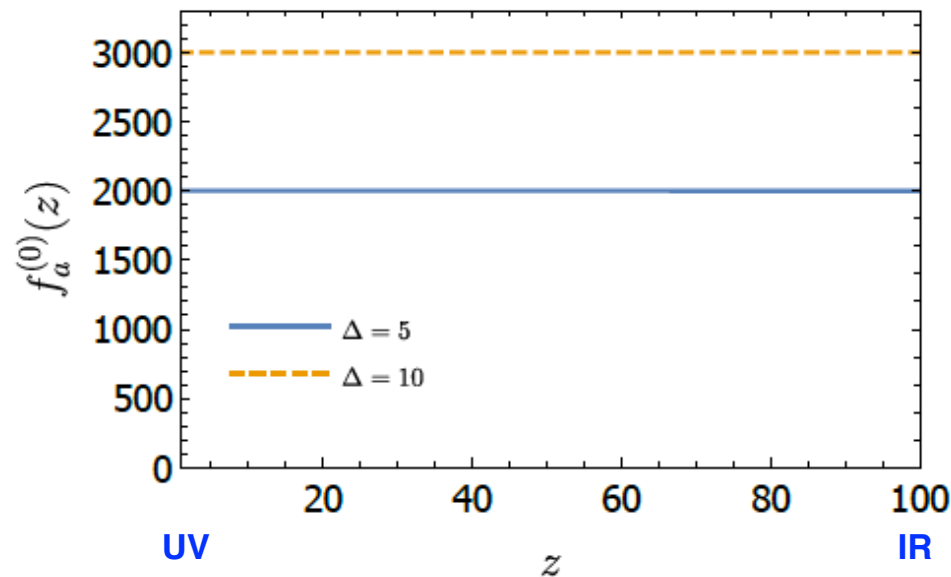
$$\sigma = \sqrt{v_{IR}^2 - \frac{\Delta}{2\lambda_{IR}}}(kz_{IR})^{-\Delta} \equiv \sigma_0(kz_{IR})^{-\Delta}$$

“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:

$$a^{(0)}(x^\mu) \rightarrow a^{(0)}(x^\mu) + \alpha_0$$

Massless axion

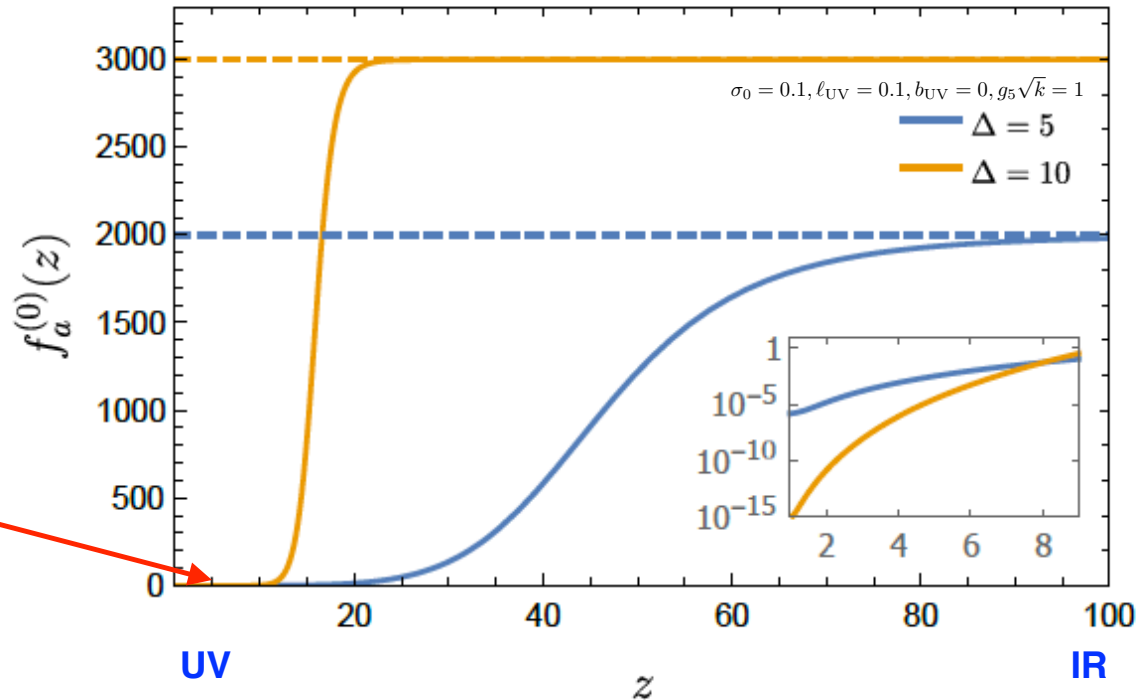
UV PQ-breaking ($\lambda \neq 0$)

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


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

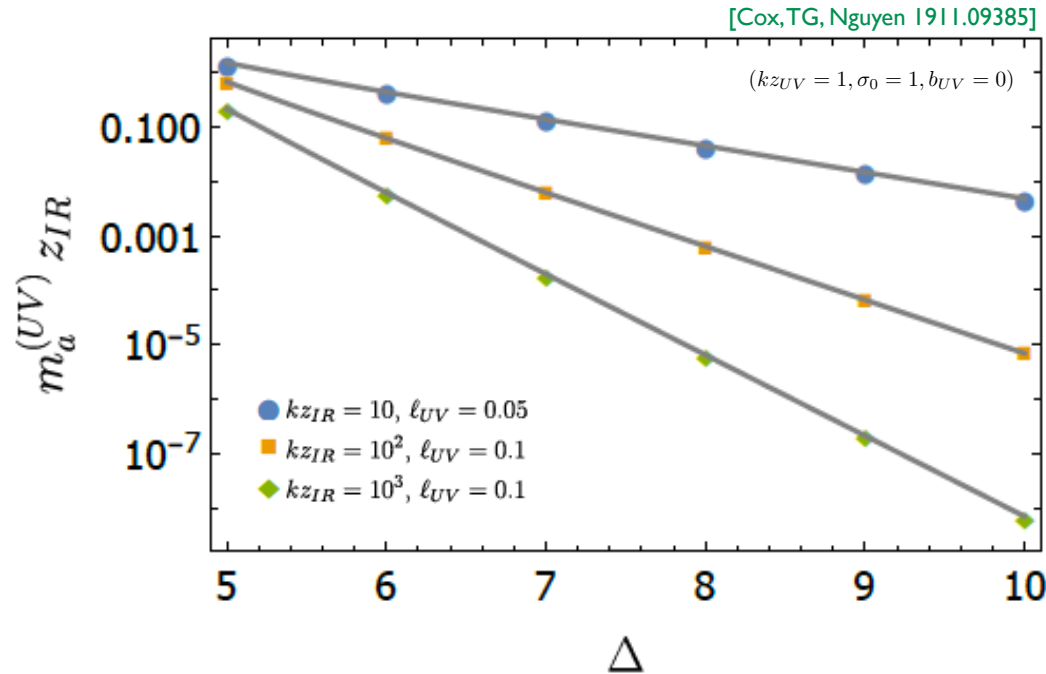
$$f_a^{(0)}(z) \simeq z_{IR} \frac{k^{3/2}}{\eta(z)} \sqrt{\Delta - 1} \left(\frac{z}{z_{IR}} \right)^\Delta \left[1 + \frac{2\lambda(\Delta - 2)(kz_{UV})^\Delta (kz)^{2(2-\Delta)}}{\ell_{UV} + 2\sigma_0(\Delta - 2)(z_{UV}/z_{IR})^\Delta} \right]$$

[Cox, TG, Nguyen 1911.09385]



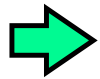
Axion profile suppressed!

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



UV axion mass suppressed for large Δ

Bulk Chern-Simons term: $-\frac{\kappa}{32\pi^2} \int_{z_{UV}}^{z_{IR}} d^5x \epsilon^{MNPQR} V_M G_{NP}^a G_{QR}^a$ ← 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

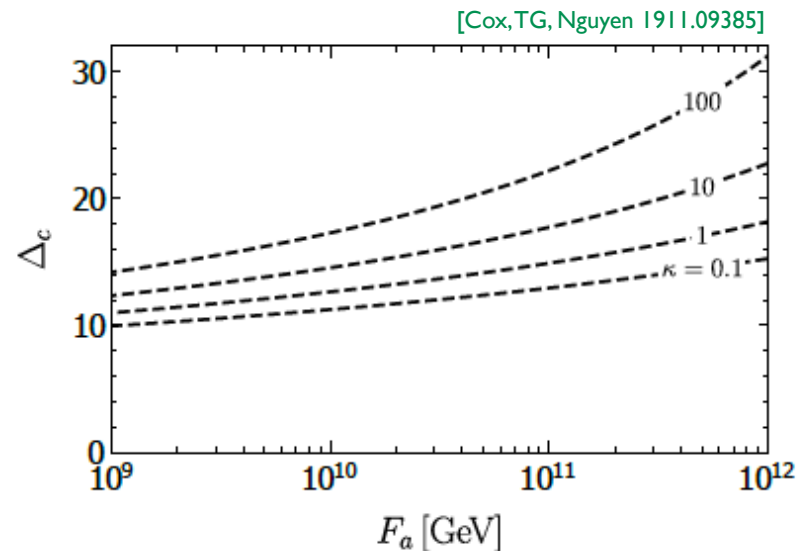
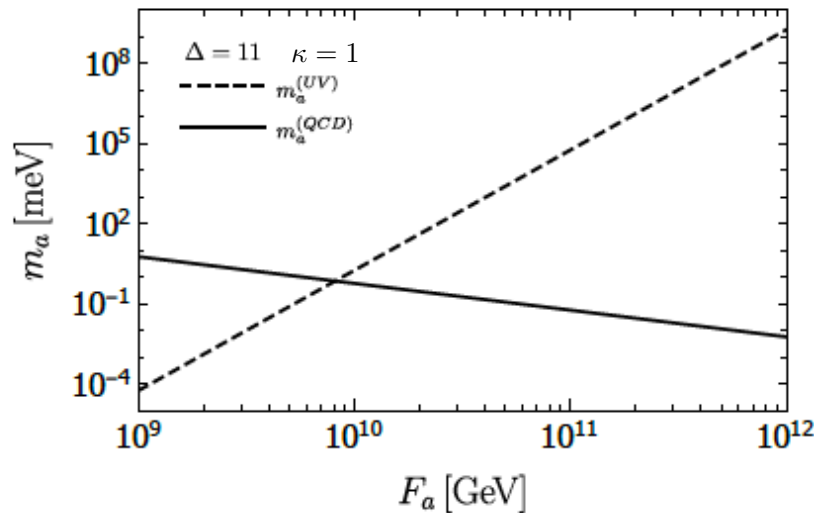
$$F_a \simeq \frac{1}{\kappa} \frac{\sigma_0}{\sqrt{\Delta-1}} z_{IR}^{-1}$$

Axion potential:

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

relative phase

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



$$10^9 \text{ GeV} \lesssim F_a \lesssim 10^{12} \text{ GeV}$$



$$\Delta_c \gtrsim 10$$



Solves
axion-quality
problem!

Holographic (AdS/CFT) interpretation:

5D

local $U(1)_{PQ}$ symmetry

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

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

$$\sigma$$

$$\lambda$$

$\leftrightarrow$

$\leftrightarrow$

$\leftrightarrow$

$\leftrightarrow$

$\leftrightarrow$

4D

global $U(1)_{PQ}$ symmetry

$\mathcal{O}$, dimension Δ

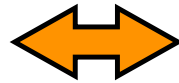
$$\Lambda_{IR} = \Lambda_{UV} e^{-\frac{8\pi^2}{b_{CFT} g^2}}$$

$$\langle \mathcal{O} \rangle$$

$$\lambda \Phi \mathcal{O}$$

Holographic interpretation:

5D axion,
local U(1) PQ symmetry



4D composite axion, accidental
global U(1) PQ symmetry

Example: [Gavela, Ibe, Quilez, Yanagida:1812.08174]

	New strong gauge group		Global symmetries		
	$SU(5)$	$SU(3)_c$	$SU(n)_5$	$SU(n)_{10}$	$U(1)_{B-L} \equiv U(1)_{PQ}$
ψ_5	$\bar{\mathbf{5}}$	$\mathbf{R}$	$\square$	$\mathbf{1}$	-3
ψ_{10}	$\mathbf{10}$	$\mathbf{R}$	$\mathbf{1}$	$\square$	1

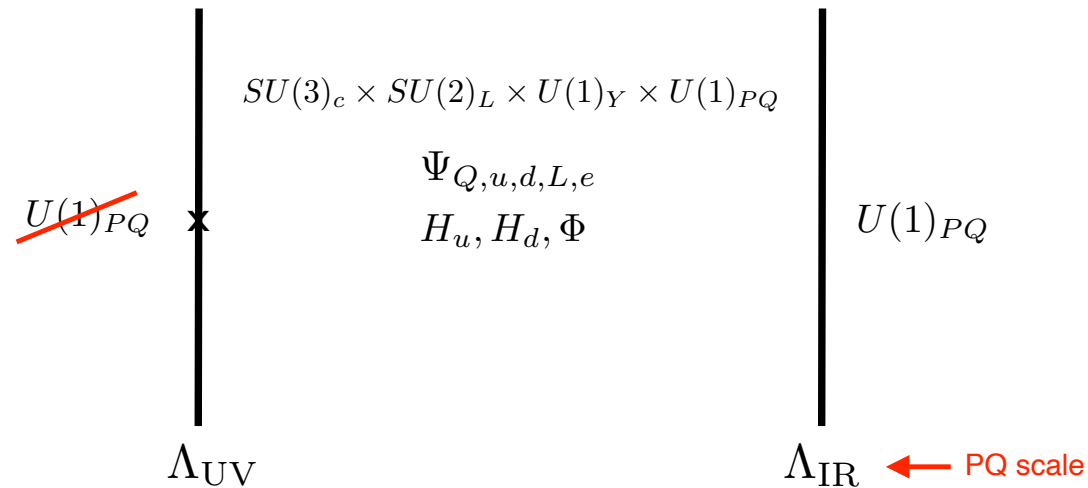
Chiral condensate: $\langle \mathbf{10} \mathbf{10} \mathbf{10} \bar{\mathbf{5}} \rangle \sim \Lambda_5^6 \implies SU(n)_5 \times SU(n)_{10} \longrightarrow G \supset SU(3)_c$

PQ condensate: $\langle \bar{\mathbf{5}} \bar{\mathbf{5}} \mathbf{10} \bar{\mathbf{5}} \bar{\mathbf{5}} \mathbf{10} \rangle \sim \Lambda_5^9$ ← dimension 9! (due to gauge invariance and chirality)

$\mathcal{L}_{PQ} = c \frac{(4\pi)^2}{2! 4!} \left(\frac{N}{5} \right)^9 \frac{f_a^9}{M_{Pl}^5} e^{-i \frac{10}{N} a / f_a} + \text{h.c.}$

Flavored Warped Axion [Bonnefoy, Cox, Dudas, TG, Nguyen 2012.09728]

Consider DFSZ-like axion model with bulk Standard Model fermions:



Bulk VEVs: constant bulk Higgs vevs

$$H_u = \frac{v_u}{\sqrt{2}} e^{i \frac{a_u(x,z)}{v_u}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad H_d = \frac{v_d}{\sqrt{2}} e^{i \frac{a_d(x,z)}{v_d}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad \Phi = \eta(z) e^{ia(x,z)}$$

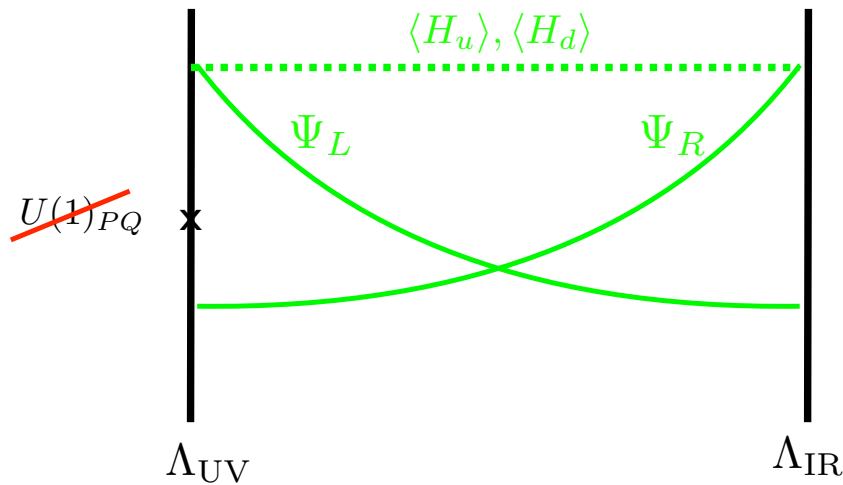
Bulk Yukawa couplings:

$$-2 \int_{z_{UV}}^{z_{IR}} d^5x \sqrt{-g} \frac{1}{\sqrt{k}} \left(y_{u,ij}^{(5)} \bar{Q}_i U_j H_u + y_{d,ij}^{(5)} \bar{Q}_i D_j H_d + y_{e,ij}^{(5)} \bar{L}_i E_j H_d + \text{h.c.} \right)$$

Bulk fermion mass:

$$m_{\Psi_i} = c_{\Psi_i} k$$

Bonus feature: explains fermion mass hierarchy [TG, Pomarol '00]

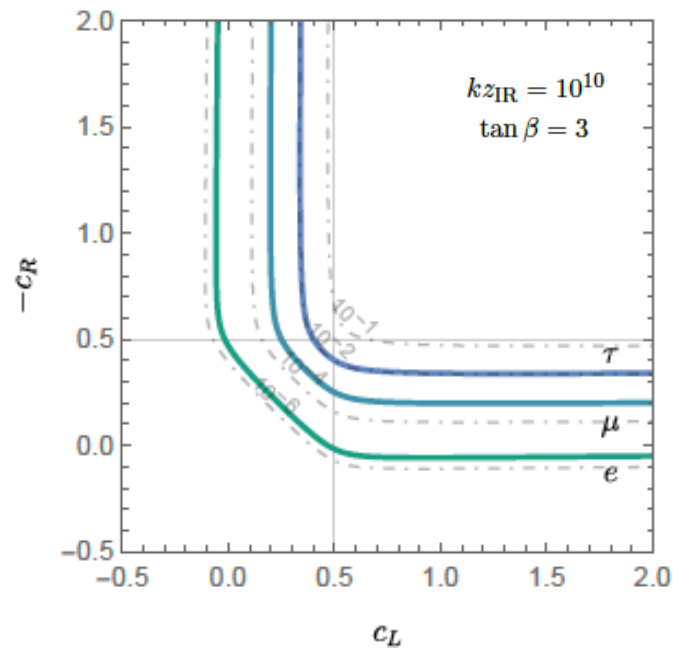
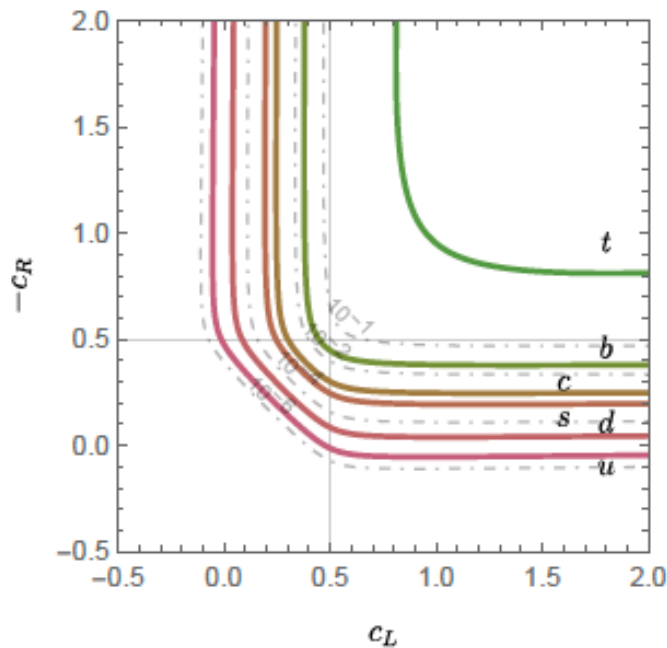


$$m_u^{ij} = y_{u,ij}^{(5)} \frac{\sqrt{2}v_u}{\sqrt{k}} \int_{z_{UV}}^{z_{IR}} \frac{dz}{(kz)^5} f_{Q_{iL}}^0(z) f_{U_{jR}}^0(z)$$

$$\left. \begin{aligned} f_{Q_{iL}}^0(z) &= \mathcal{N}_{Q_i} (kz)^{2-c_{Q_i}} \\ f_{U_{iR}}^0(z) &= \mathcal{N}_{U_i} (kz)^{2+c_{U_i}} \end{aligned} \right\} \text{bulk fermion mass parameters}$$

(similarly $m_{d,e}^{ij}$)

← PQ scale



Axion-fermion couplings:

$$i \int d^4x \frac{\partial_\mu a^0}{2F_a} (\bar{u}_i \gamma^\mu ((c_u^V)_{ij} - (c_u^A)_{ij} \gamma^5) u_j)$$

$$A_L^u m_u^{ij} A_R^{u\dagger} = m_{u_i} \quad (\text{similarly for down-type quarks and leptons})$$



Overlap between axion and fermion profiles

$$(c_u^{V,A})_{ij} = X_{H_u} \int_{z_{UV}}^{z_{IR}} \frac{dz}{(kz)^4} g_a^0(z) \left((A_R^u)_{ik} (f_{U_{kR}}^0)^2 (A_R^{u\dagger})_{kj} \mp (A_L^u)_{ik} (f_{Q_{kL}}^0)^2 (A_L^{u\dagger})_{kj} \right)$$

Axion profile:

$$f_a^0(z) = \frac{1}{F_a} (1 + \underbrace{g_a^0(z)}_{\text{z-dependent part of axion profile depends on } \Delta})$$

z-dependent part of axion profile depends on Δ

SM fermion profiles:

$$f_{Q_{iL}}^0(z) = \mathcal{N}_{Q_i} (kz)^{2-c_{Q_i}},$$

(similarly for leptons)

$$f_{U_{iR}}^0(z) = \mathcal{N}_{U_i} (kz)^{2+c_{U_i}},$$

$$f_{D_{iR}}^0(z) = \mathcal{N}_{D_i} (kz)^{2+c_{D_i}}.$$

Parameter count:

9 $c_{Q_i}, c_{u_i}, c_{d_i}$ parameters - (6 quark masses + 2 CKM) = 1 free parameter ($c_{Q_3} + c_{u_3}$)

6 c_{L_i}, c_{e_i} parameters - (3 charged lepton masses + 2 PMNS) = 1 free parameter ($c_{L_3} + c_{e_3}$)

(assuming, for simplicity, PMNS generated in charged lepton sector)

{ Majorana neutrino-axion model [Cox,TG, Nguyen: 2107.14018] $\rightarrow$ light sterile neutrinos }

Numerical results

Flavor-violating couplings:

$$\frac{1}{(F_u^{V,A})_{ij}} \equiv \frac{(c_u^{V,A})_{ij}}{F_a}$$

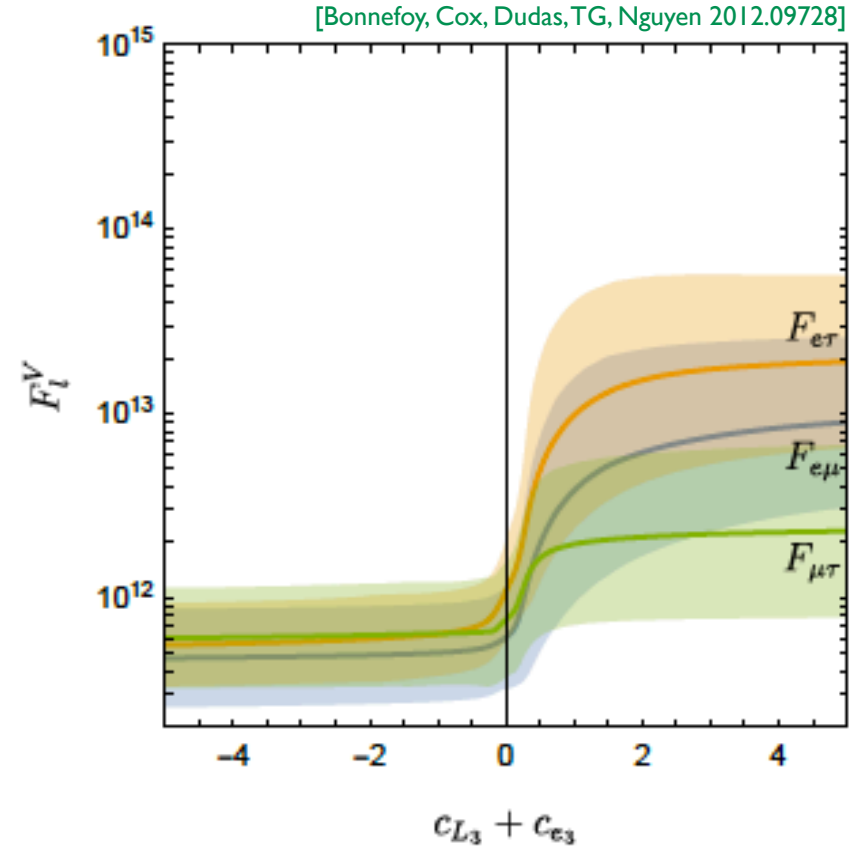
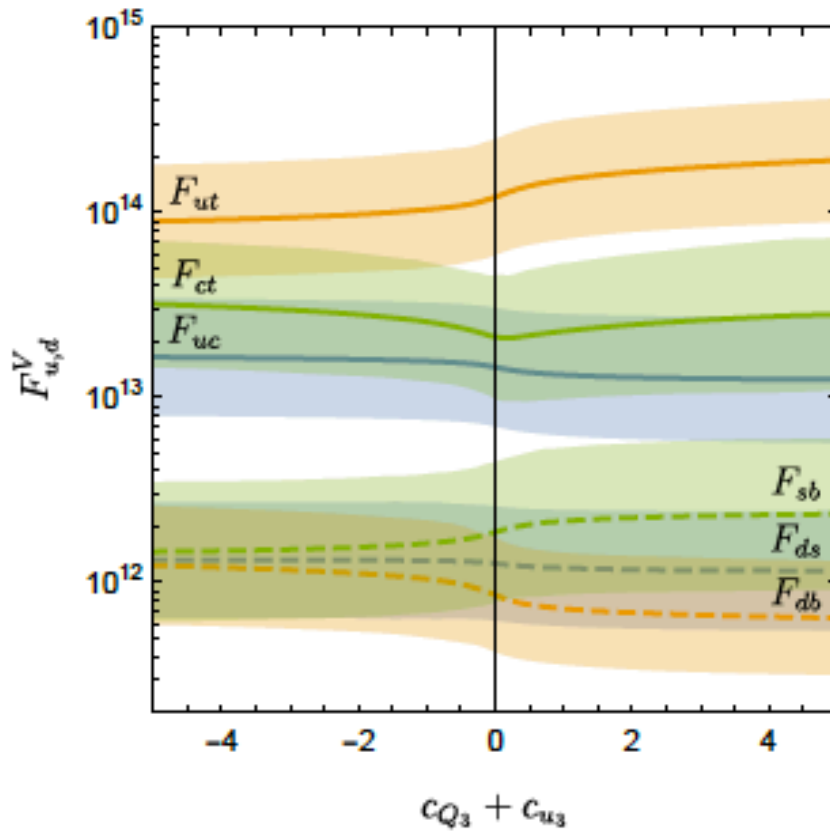
$$F_{u,d,\ell}^A \approx \mathcal{O}(F_{u,d,\ell}^V)$$

$$kz_{\text{IR}} = 10^{10}, g_5^2 k = 1.$$

$$\Delta = 10 \quad \sigma_0 = 3.$$

$$F_a \simeq 10^9 \text{ GeV}.$$

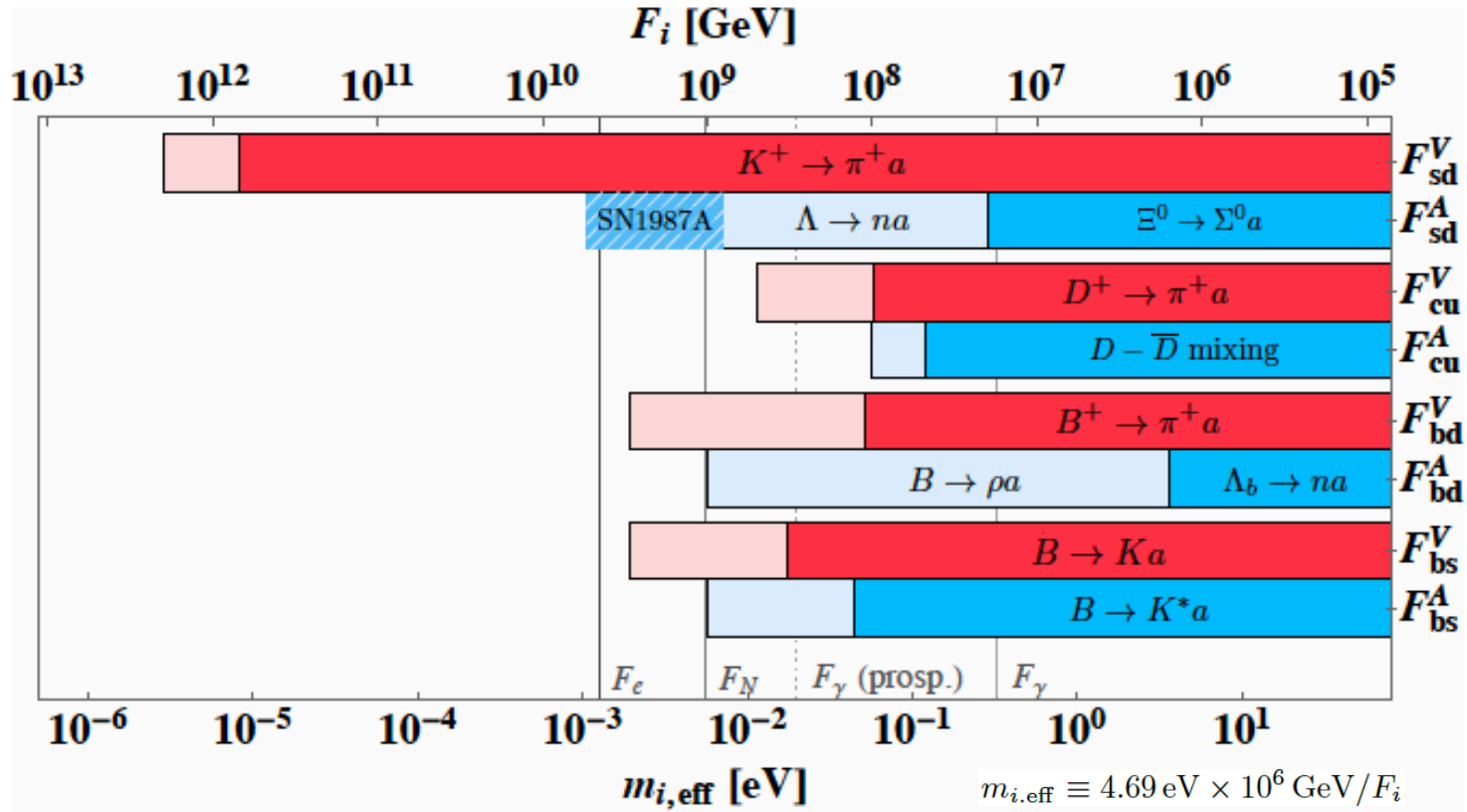
Scan over $y_{u,d,e}^{(5)} \sim 1$

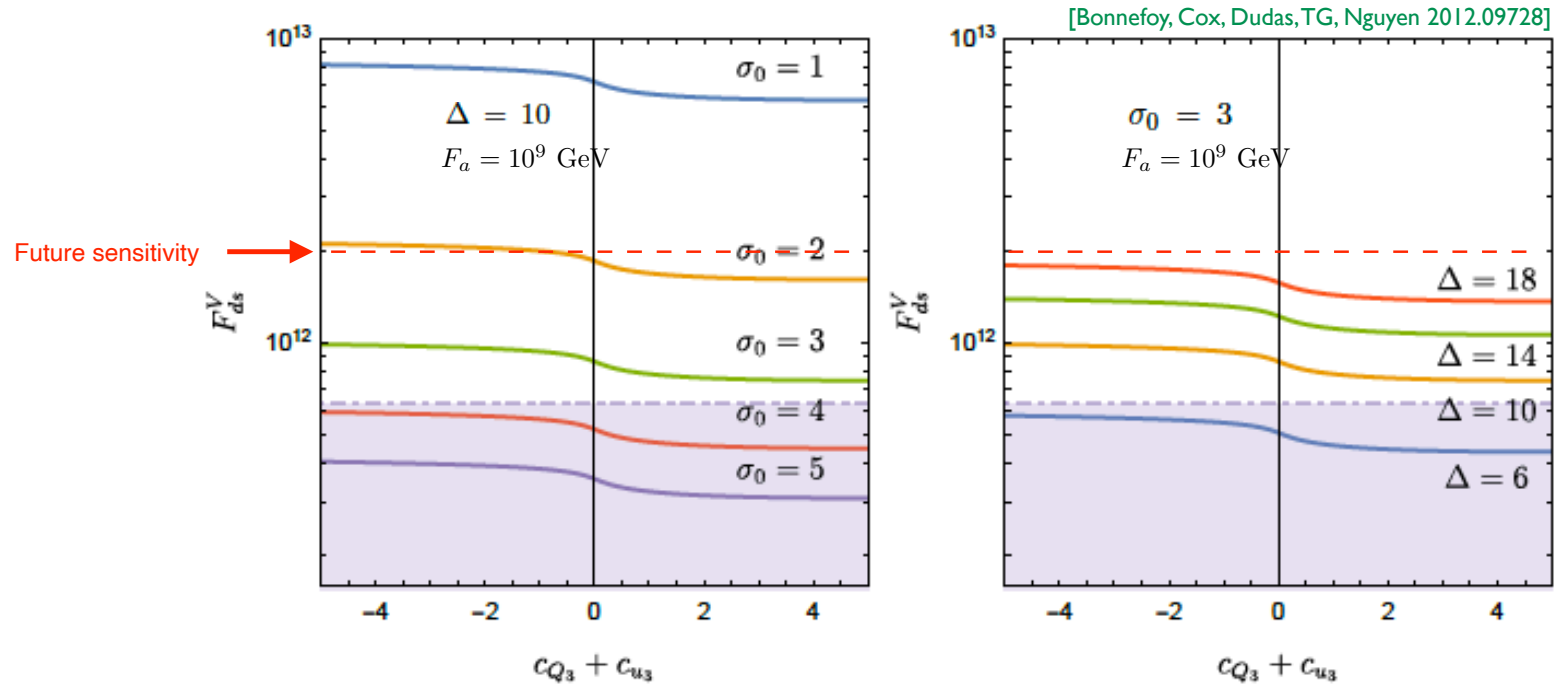


[Bonnefoy, Cox, Dudas, TG, Nguyen 2012.09728]

Limits on axion-quark couplings

[Martin Camalich, Pospelov, Vuong, Ziegler, Zupan: 2002.04623]





Experimental limits : $(F_d^V)_{12} \gtrsim 6.8 \times 10^{11} \text{ GeV}$ ($K^+ \rightarrow \pi^+ a$ decays)

[Martin Camalich, Pospelov, Vuong, Ziegler, Zupan 2002.04623]

$\Rightarrow \sigma_0 \gtrsim 4, \quad \Delta \gtrsim 6$

2. Axion mass from 5D small instantons

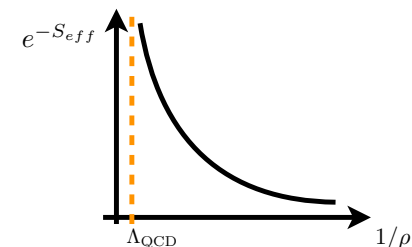
[TG, Khoze, Pomarol, Shirman: 2001.05610]

QCD axion mass:

$$m_a^2 = \frac{\mathcal{T}}{f_a^2} \quad \mathcal{T} \equiv -i \int d^4x \langle 0 | T \left[\frac{1}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}(x), \frac{1}{32\pi^2} G_{\rho\sigma}^b \tilde{G}^{b\rho\sigma}(0) \right] | 0 \rangle \quad \text{“topological susceptibility”}$$

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



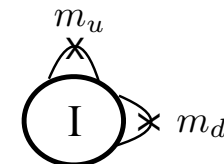
$$\mathcal{T} \propto \Lambda_{QCD}^4$$

“Large instantons”

$$\rho \sim 1/\Lambda_{QCD}$$

Fermion zero modes:

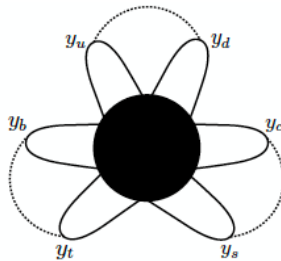
$$(\rho m_f)^{N_f} \longrightarrow \text{suppression} \quad \frac{\prod_f m_f}{\Lambda_{QCD}^{N_f}}$$



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

How to enhance 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



$$\kappa_f = \frac{y_u}{4\pi} \frac{y_d}{4\pi} \frac{y_c}{4\pi} \frac{y_s}{4\pi} \frac{y_t}{4\pi} \frac{y_b}{4\pi} \approx 10^{-23} \quad (\text{otherwise } \frac{m_u m_d m_c m_s m_b m_t}{\Lambda_{UV}^6})$$



$$m_a^2 f_a^2 \sim \frac{1}{8} \Lambda_{\text{QCD}}^4 + \Lambda_I^4$$

new contribution

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

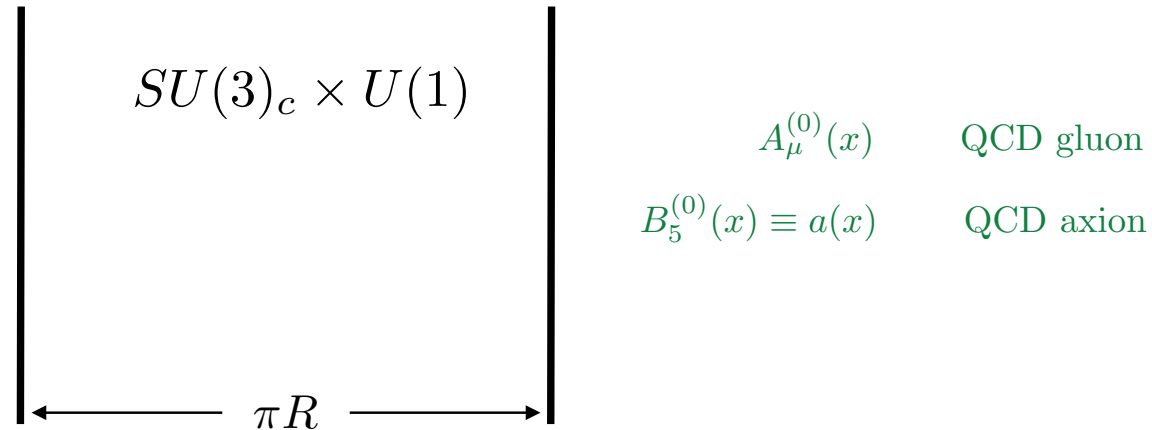
Use 5th dimension to make QCD axion heavy!

QCD in 5D

Flat space 5D metric:

$$ds^2 = dx^2 + dy^2$$

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



5D instanton:

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

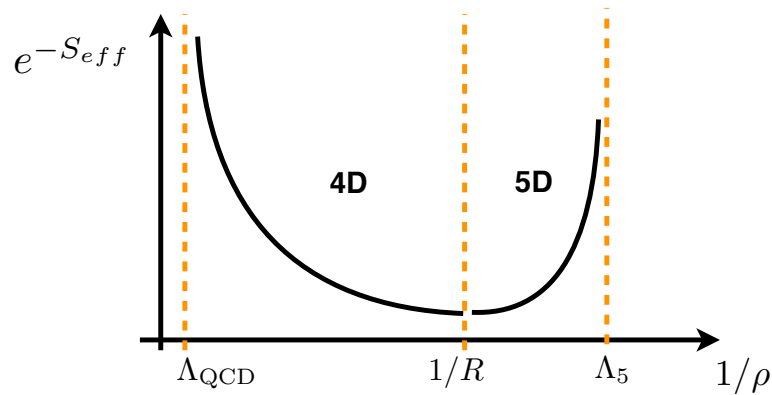


$$S_5^{(I)} = \frac{8\pi^3 R}{g_5^2} = \frac{2\pi}{\alpha_s}$$

Finite action

5D small instantons

Fluctuations + Kaluza-Klein contributions



small instantons!

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



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

power law term!

$\xi(R/\rho) \sim 1/3$
 $R/\rho \gtrsim 20$

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

power law contribution can overcome suppression

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

Axion mass from 5D small instantons

Assume boundary Standard Model fermions ($b_0 = 7$) and QCD in bulk

Yukawa coupling suppression from Higgs loops

5D enhancement

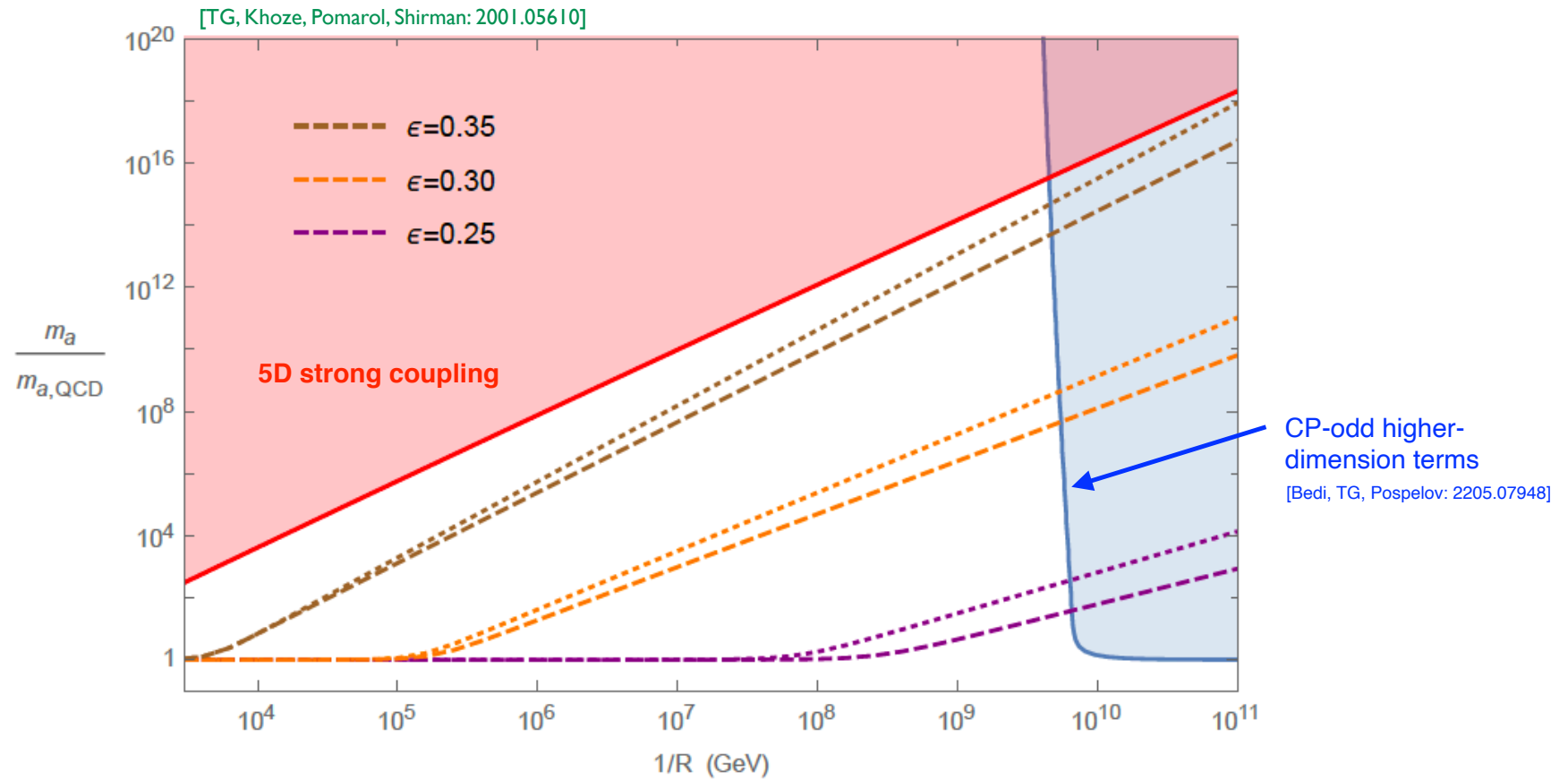


$$\frac{m_a}{m_{a,QCD}} \simeq \sqrt{2\kappa_f C[3]} \left(\frac{2\pi}{\alpha_s(1/R)} \right)^3 \frac{(m_u + m_d)}{\sqrt{m_u m_d}} \frac{1}{m_\pi f_\pi R^2} \frac{e^{-\frac{1}{2} \left(\frac{2\pi}{\alpha_s(1/R)} - \Lambda_5 R \right)}}{(\Lambda_5 R)^{\frac{1}{2}(b_0-3)}}$$

Write $\Lambda_5 R = \frac{6\pi\varepsilon}{\alpha_s(1/R)}$ where $\varepsilon \lesssim 1$ (perturbativity limit)

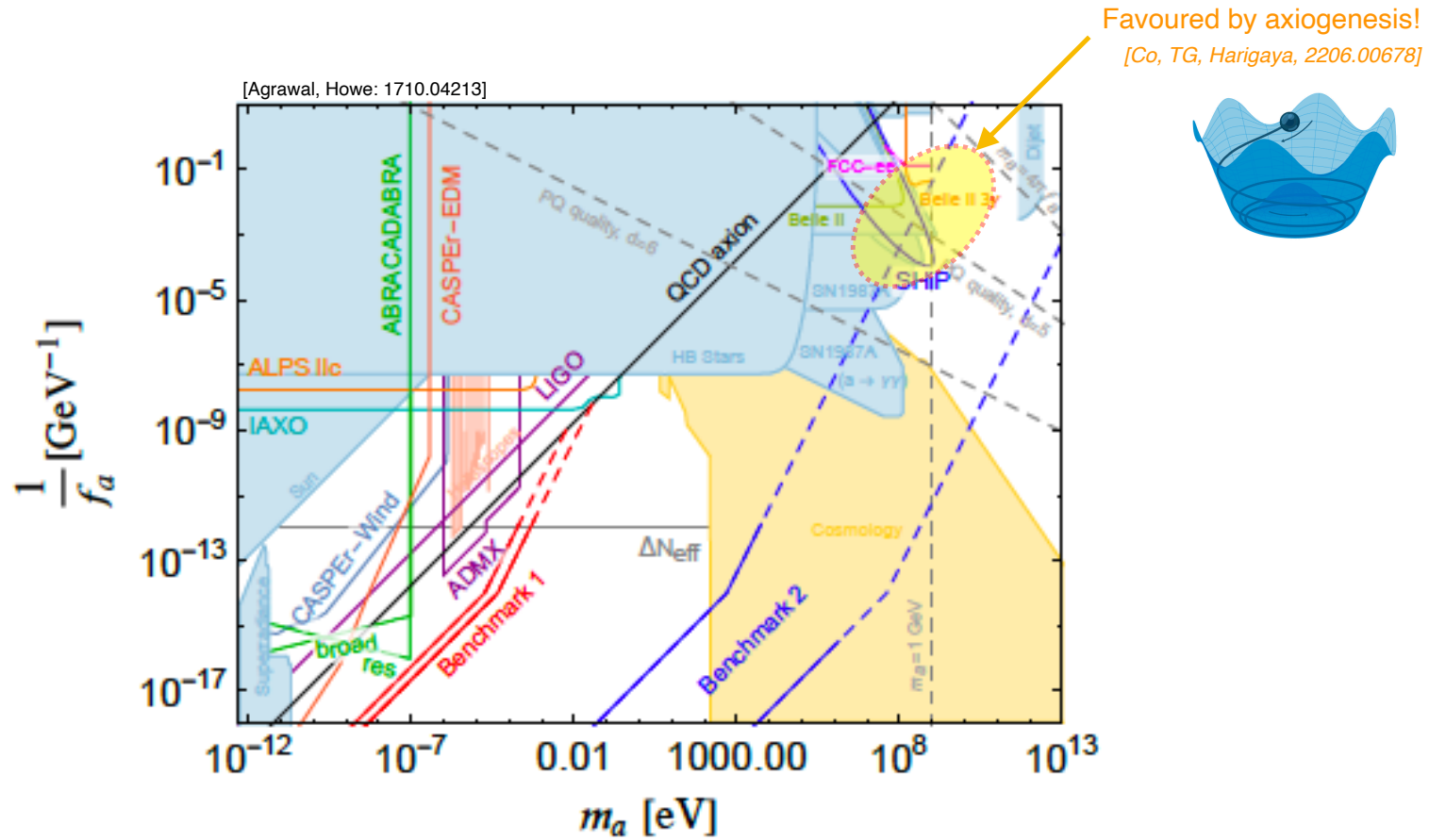
Positive exponent: $\frac{2\pi}{\alpha_s(1/R)} - \Lambda_5 R < 0 \quad \Rightarrow \quad \varepsilon \gtrsim 0.14$

Maximum axion mass enhancement: $m_{a,5f}^2 \sim \kappa_f \frac{\Lambda_5^4}{f^2}$



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

Heavy Axion Limits



Heavy QCD axion (1 MeV – 10 GeV)
solves strong CP + baryon asymmetry!

Other possibilities:



Strong QCD

[Holdom, Peskin 1982] [Flynn, Randall 1987]



Enlarge QCD color

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

[Dimopoulos, Susskind '79; Dimopoulos '79]

$$SU(3 + N) \times SU(N)' \rightarrow SU(3)_c \times SU(N)_D$$

[TG, Nagata Shifman: 1604.01127]

[Gaillard, Gavela, Houtz, Quilez, del Rey: 1805.06465]

$$SU(3)_1 \times SU(3)_2 \times \cdots \times SU(3)_k \rightarrow SU(3)_c$$

[Agrawal, Howe 1710.04213]

[Csaki, Ruhdorfer, Shirman 1912.02197]

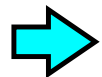


Mirror QCD

[Rubakov '97] [Berezhiani, Gianfagna, Gianotti '00]

[Dimopoulos, Hook, Huang, Marques-Tavares: 1606.03097]

[Hook, Kumar, Liu, Sundrum: 1911.12364]



Axion mass is sensitive to UV completion!

Questions/Future Work

- Generalize to z-dependent bulk Higgs VEVs
— could enhance specific axion-fermion couplings
- Construct 4D dual models with $\Delta \geq 10$
- Dark matter ALPs with axion-fermion couplings?
- Small instantons in weakly-gauged holographic models

[TG, Pomarol: 2110.01762]

$$A_\mu^a(x, z) = 2\eta_{\mu\nu}^a \frac{x_\nu}{x^2} \frac{(x^2 + z^2)^2}{x^2 \rho^2 + (x^2 + z^2)^2}$$

New “localized” instanton
anti-instanton solution!

— other solutions that give axion mass enhancement?

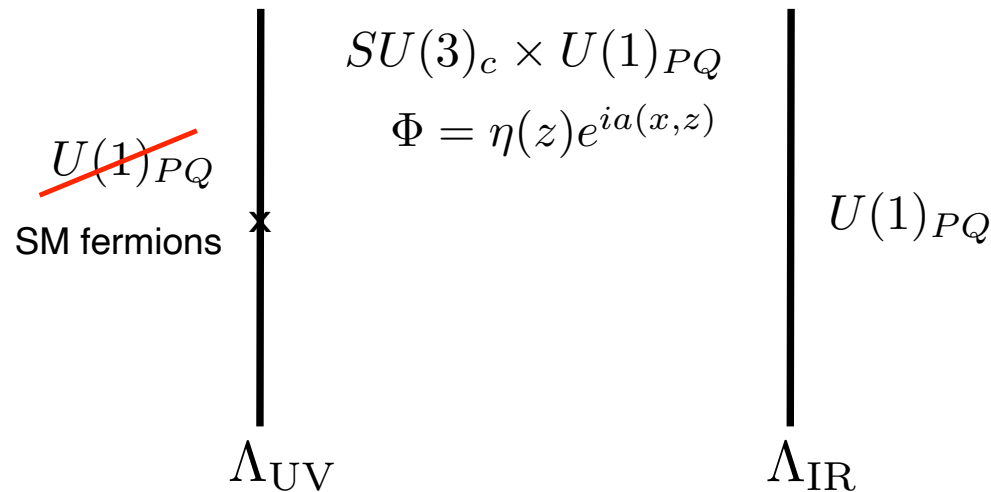
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Summary

- Axion quality problem can be solved in 5D warped dimension
 - *dual to 4D dynamical axion with accidental PQ symmetry*
- “Flavored” warped axion
 - *solves axion quality and explains fermion mass hierarchy*
 - *predicts flavor-violating axion-fermion couplings*
 - *light sterile neutrinos*
- 5D small instantons
 - *can enhance axion mass and not spoil strong CP solution*
 - *axion mass could be a sensitive probe of UV physics!*

Extra Slides

Axion-Gluon Coupling



Bulk Chern-Simons term: $-\frac{\kappa}{32\pi^2} \int_{z_{UV}}^{z_{IR}} d^5x \epsilon^{MNPQR} V_M G_{NP}^a G_{QR}^a$ ← generates axion-gluon coupling

Under 5D gauge transformation: $V_M \rightarrow V_M + \partial_M \alpha$

➡
$$\delta S = -\frac{\kappa}{32\pi^2} \left[\int_{z_{UV}}^{z_{IR}} d^4x \alpha(x^\mu, z) \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a \right]$$

Add IR boundary term:

$$\frac{\kappa}{32\pi^2} \int d^4x a G \tilde{G} \Big|_{z_{IR}}$$

Obtain:

$$\mathcal{S}_{eff} = \int d^4x \left(\frac{1}{2} a^{(0)} (\square - m_a^2) a^{(0)} + \frac{g_s^2}{32\pi^2 F_a} a^{(0)} G \tilde{G} \right)$$

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



$$(m_a^{(UV)})^2 = \frac{4\ell_{UV}\sigma_0(\Delta-2)}{\kappa^2(\Delta-4+b_{UV})} \left(\frac{\kappa\sqrt{\Delta-1}}{\sigma_0} \right)^\Delta \underbrace{\left(\frac{F_a}{\Lambda_{UV}} \right)^{\Delta-4}}_{\text{(suppression for } F_a \ll \Lambda_{UV} \text{ and } \Delta > 4)} F_a^2$$

(suppression for $F_a \ll \Lambda_{UV}$ and $\Delta > 4$)

Numerical results

$$\frac{1}{(F_u^{V,A})_{ij}} \equiv \frac{(c_u^{V,A})_{ij}}{F_a}$$

$$kz_{\text{IR}} = 10^{10}, g_5^2 k = 1.$$

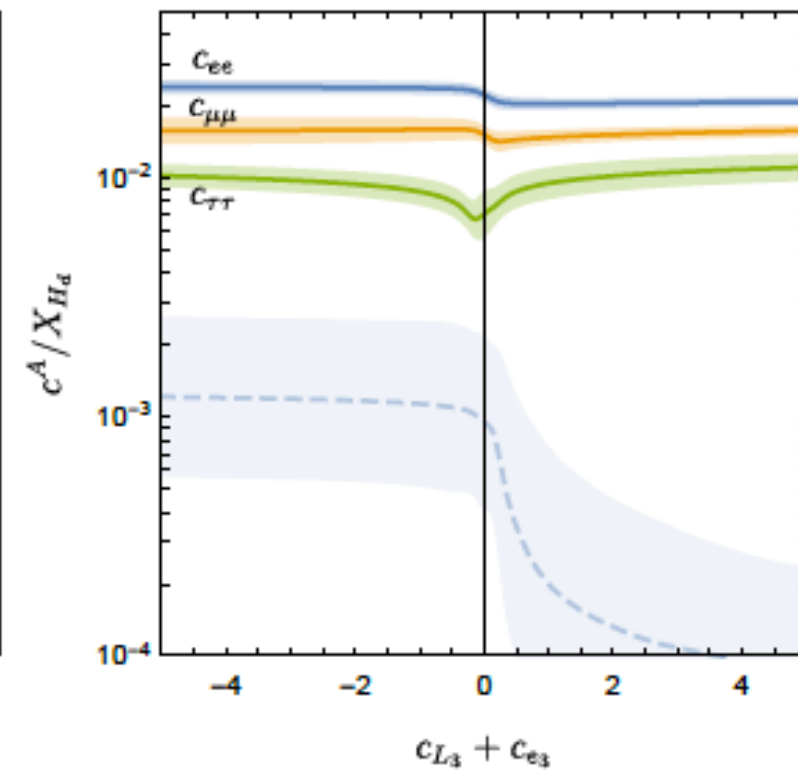
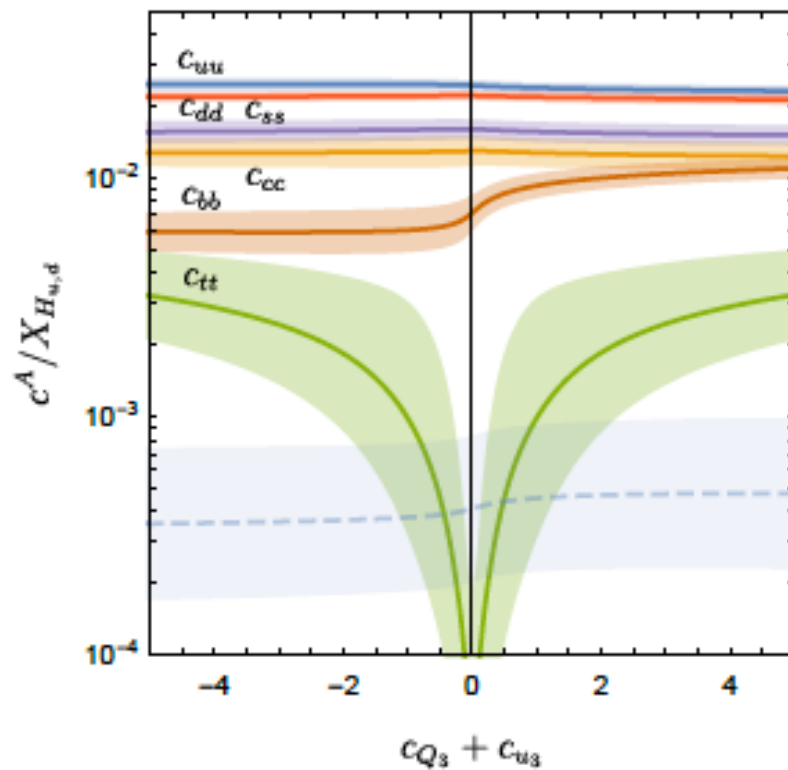
$$\Delta = 10 \quad \sigma_0 = 3,$$

$$F_a \simeq 10^9 \text{ GeV}.$$

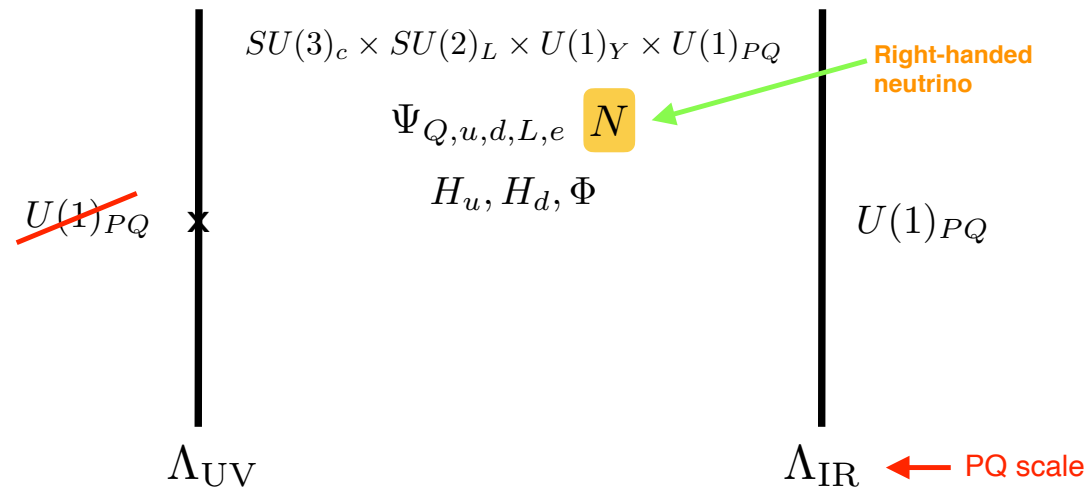
$$\text{Scan over } y_{u,d,e}^{(5)} \sim 1$$

Flavor-preserving couplings:

[Bonnefoy, Cox, Dudas, TG, Nguyen 2012.09728]



Neutrino-Axion Model [Cox, TG, Nguyen: 2107.14018]



Bulk Yukawa coupling: $\frac{1}{\sqrt{k}} \left(y_{\nu,ij}^{(5)} \bar{L}_i N_j H_u + y_{e,ij}^{(5)} \bar{L}_i E_j H_d + \text{h.c.} \right)$ ← PQ charge of N forbids bulk Majorana terms

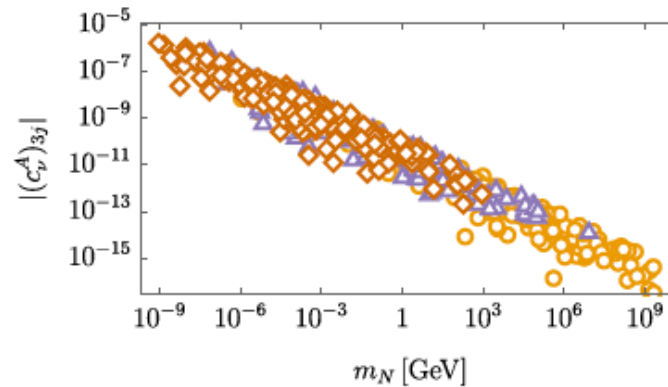
UV boundary: $\frac{1}{2} \left(b_{N,ij} \bar{N}_i^c N_j + \frac{y_{N,ij}^{(5)}}{k^{3/2}} \Phi \bar{N}_i^c N_j + \text{h.c.} \right)$

Predictions:

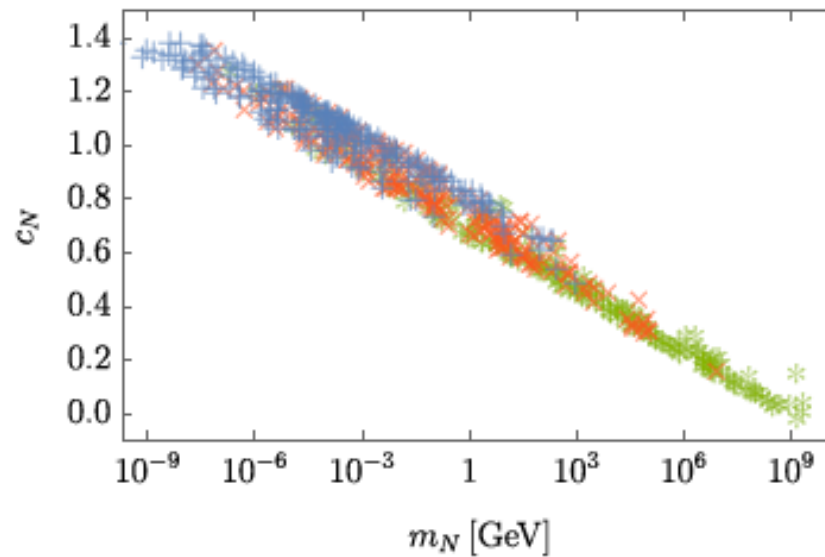
Parameters chosen to explain axion quality, neutrino mass differences and PMNS angles

$$\sigma_0 = 0.1, \lambda = 0.1, \Delta = 10, \tan \beta = 3, k z_{\text{IR}} = 10^7 \quad \Rightarrow \quad F_a \simeq 8.12 \times 10^9 \text{ GeV}$$

♦ Axion-neutrino couplings



♦ Light sterile neutrinos!



$$\Rightarrow 1 \text{ eV} \lesssim m_N \lesssim 10^9 \text{ GeV}$$

Higher dimension terms:

$$\Delta S_5 = -\frac{1}{4g_5^2} \int d^4x \int_0^L dy \frac{c_6}{\Lambda_5^2} \text{Tr } G_{MN} \square G^{MN}$$



$$S_{\text{eff}} = \frac{2\pi}{\alpha_s} + \boxed{\frac{3\pi}{\alpha_s} \frac{c_6}{(\Lambda_5 \rho)^2}} - 3\xi(R/\rho) \frac{R}{\rho} + \dots$$

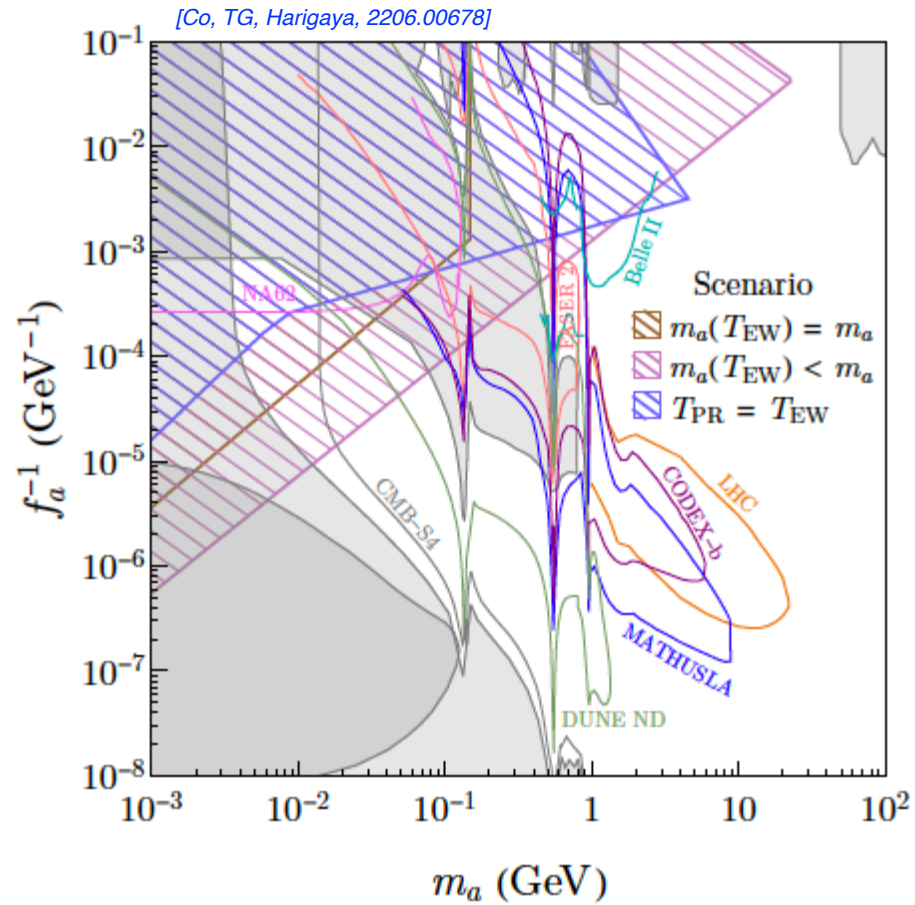
Higher dimension contribution

Extremum:
($c_6 > 0$)

$$\frac{1}{\rho_*} \simeq \frac{3}{c_6} \xi(R/\rho) \left(\frac{g_5^2 \Lambda_5}{24\pi^3} \right) \Lambda_5$$

Provided $\frac{g_5^2 \Lambda_5}{24\pi^3} \ll 1 \quad \Rightarrow \quad \rho_* \gg \frac{1}{\Lambda_5}$

i.e. instantons of size near UV cutoff (Λ_5) are suppressed



Heavy QCD axion solves strong CP + baryon asymmetry!