

A Holographic View of the QCD axion

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Strong CP problem

$$\mathcal{L}_{QCD} \supset \theta G\tilde{G}$$

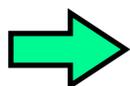
CP-odd term

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

Observable effect:

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

$$|d_N| \lesssim 3 \times 10^{-26} e \cdot \text{cm}$$



$$\bar{\theta} \lesssim 10^{-10}$$

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, Vonk: 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 $\langle \Phi \rangle = \frac{f_a}{\sqrt{2}}$

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

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

solves strong CP problem!

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

topological susceptibility

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

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

$V(a) = V_{\text{QCD}}(a) - \frac{|c_n| f_a^n}{M_P^{n-4}} \cos\left(\frac{na}{f_a} + \delta_n\right) \Rightarrow \text{minimum: } \theta_{\text{eff}} \neq 0!$

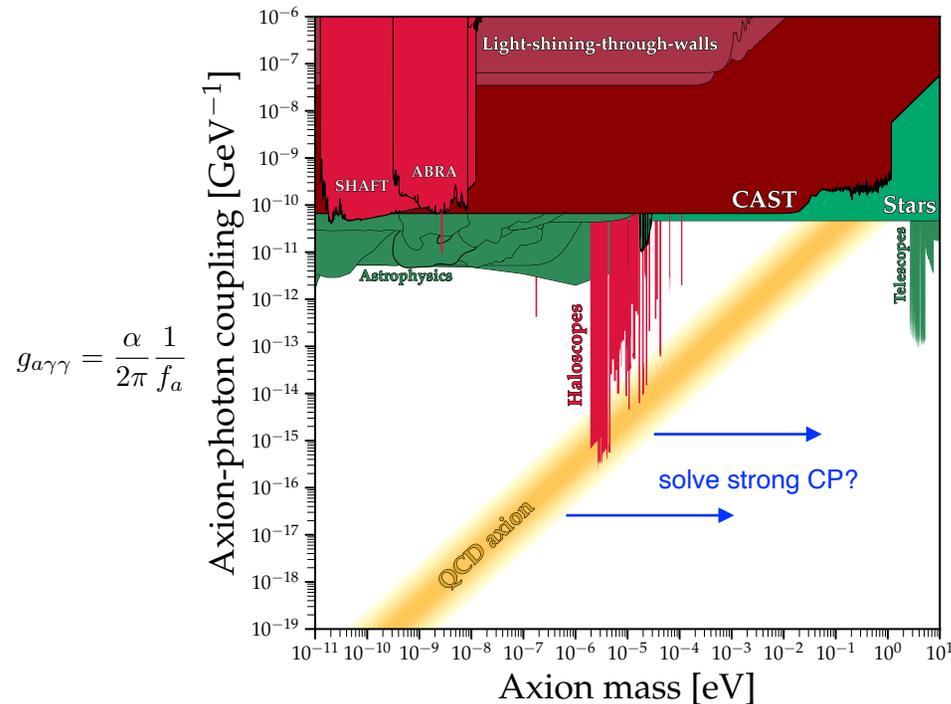
axion quality problem

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

[Note: gravitational instantons $c_n \sim e^{-S} \rightarrow S \geq 200$ but $S \sim \log \frac{M_P}{f_a \sqrt{g_s}} \sim \frac{3}{2} \log \frac{1}{g_s}$ for dynamical radial mode] [Alvey, Escudero: 2009.03917]

Questions

- How to solve the axion quality problem?
- Can the QCD axion mass be different?



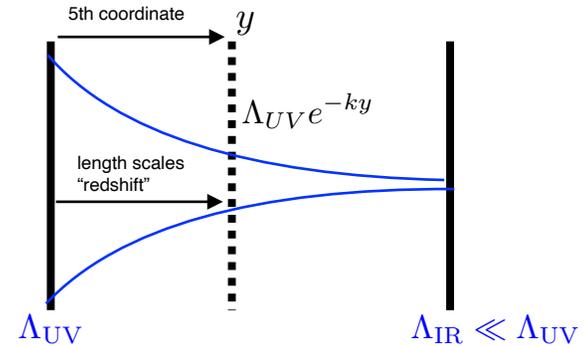
➡ Use 5th dimension to address these questions!

Why use the 5th dimension?

- ◆ Can generate a hierarchy of scales!



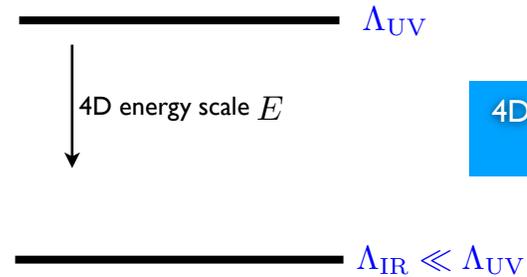
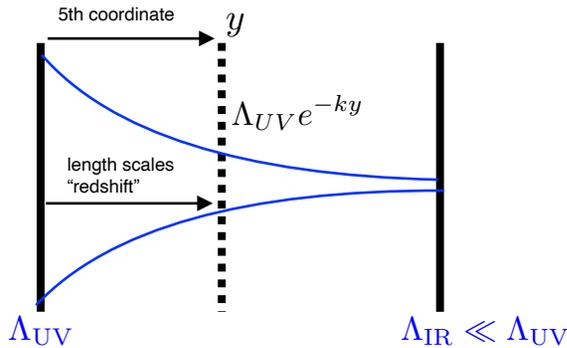
5D AdS



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

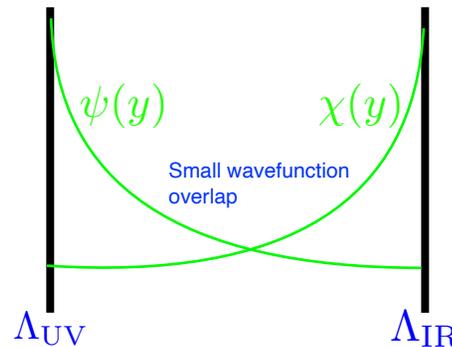


5D AdS



4D strongly-coupled gauge theory

- ◆ Can generate small couplings!

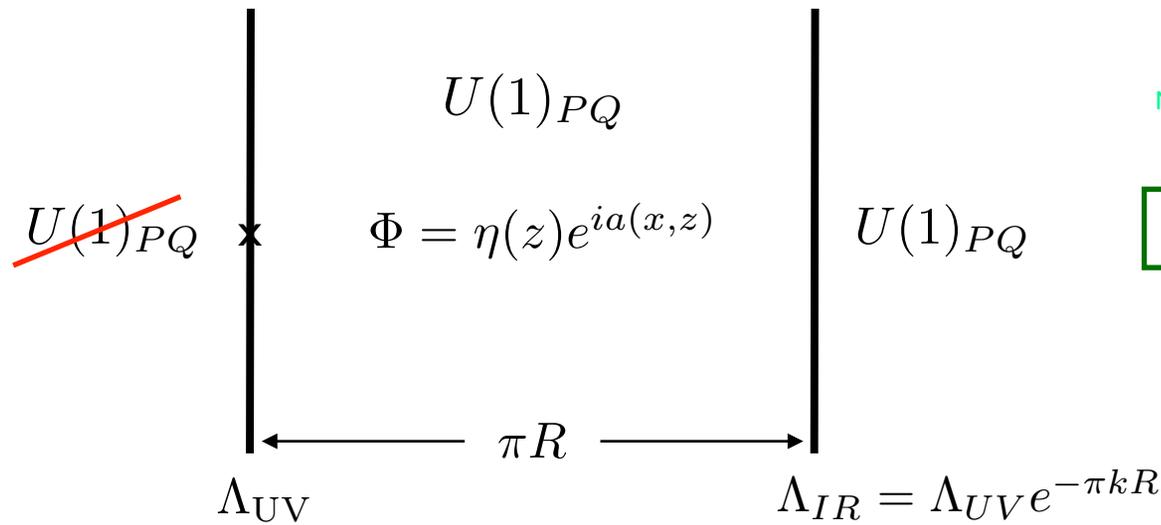


I. Axion Quality Problem [Cox, TG, Nguyen 1911.09385]

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”

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

“explicit” breaking

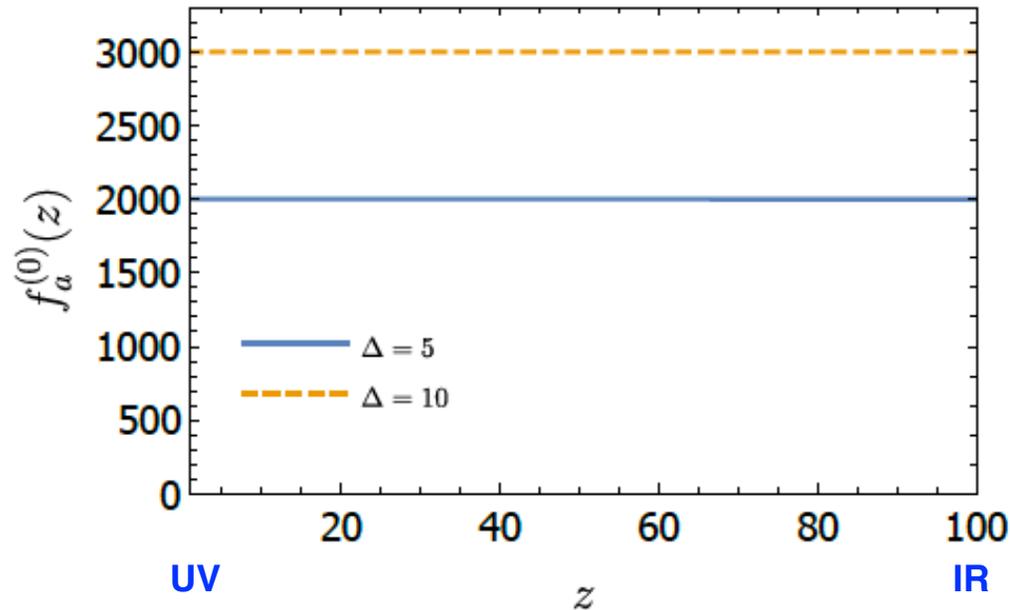
$$\sigma = \sqrt{v_{IR}^2 - \frac{\Delta}{2\lambda_{IR}}} (kz_{IR})^{-\Delta} \equiv \sigma_0 (kz_{IR})^{-\Delta}$$

“spontaneous” breaking

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

→
($z_{IR} \gg z_{UV}$)

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



Global $U(1)_{PQ}$ symmetry:

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

Massless axion

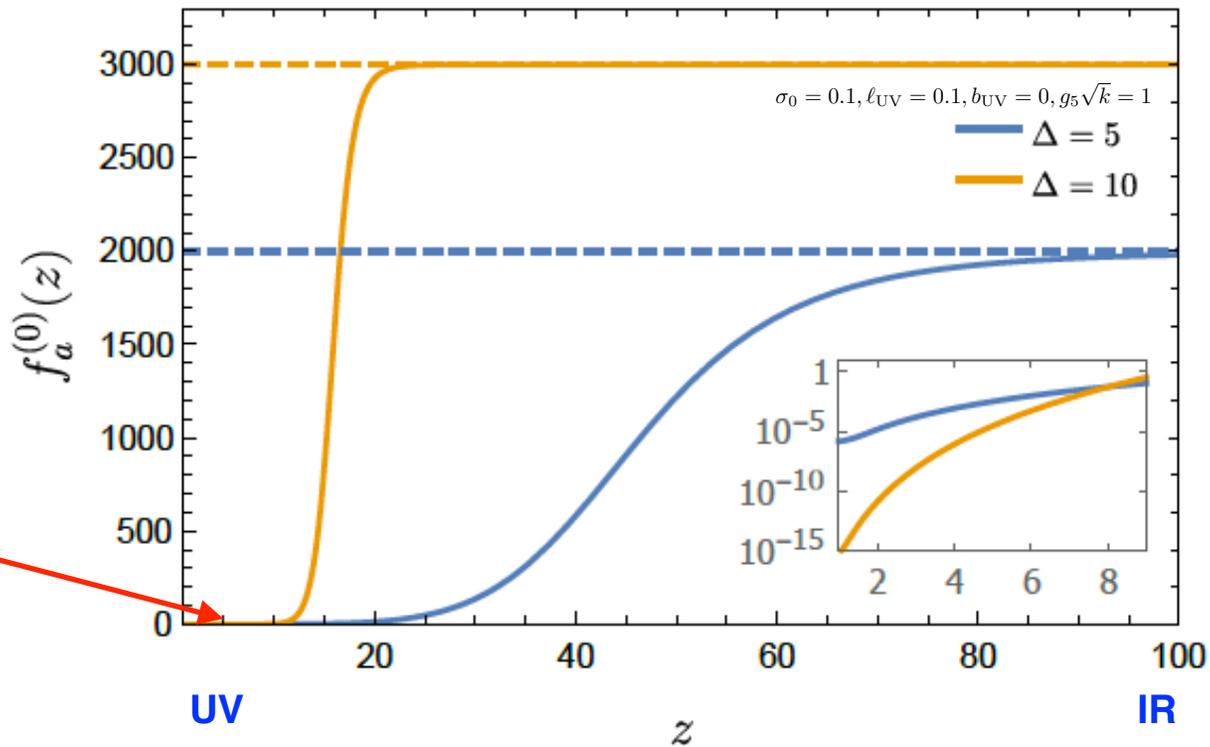
UV PQ-breaking ($\lambda \neq 0$)

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


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

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

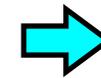
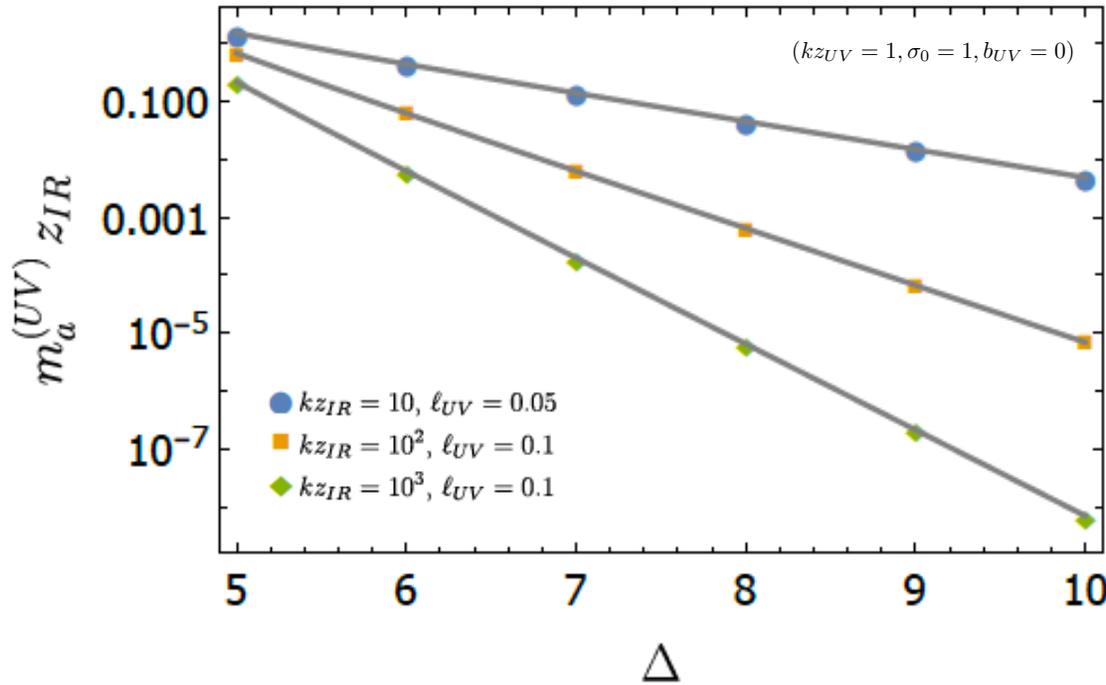
[Cox, TG, Nguyen 1911.09385]



Axion profile suppressed!

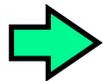
UV axion mass ($\lambda \neq 0$)

[Cox, TG, Nguyen 1911.09385]



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



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

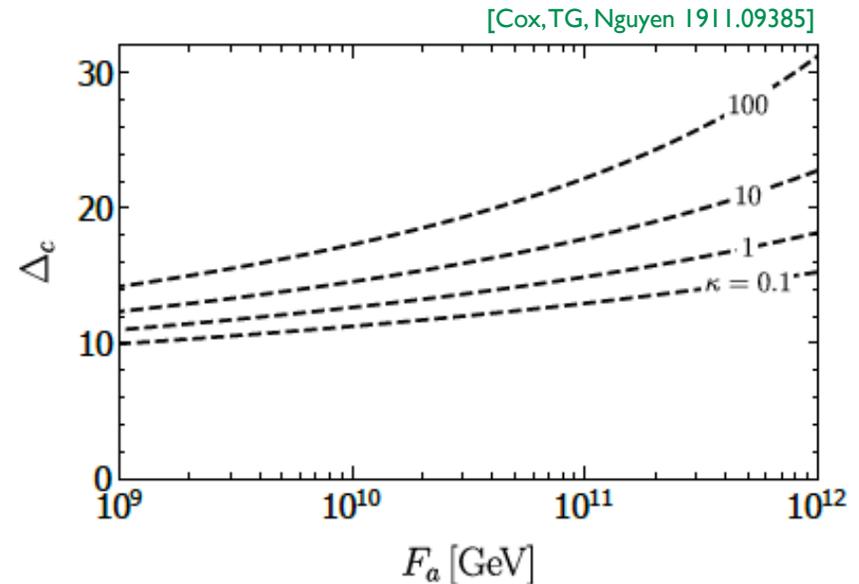
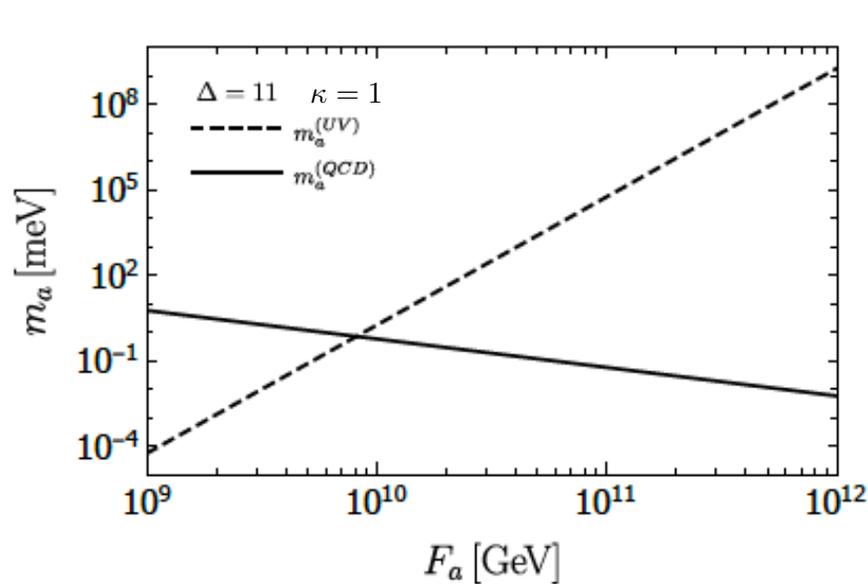
where

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

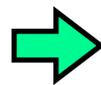
Axion potential:

$$V(a^{(0)}) \simeq -(m_a^{(QCD)})^2 F_a^2 \cos\left(\frac{a^{(0)}}{F_a} + \bar{\theta}\right) - \underbrace{(m_a^{(UV)})^2}_{\text{UV explicit PQ violation}} F_a^2 \cos\left(\frac{a^{(0)}}{F_a} + \underbrace{\delta}_{\text{relative phase}}\right)$$

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



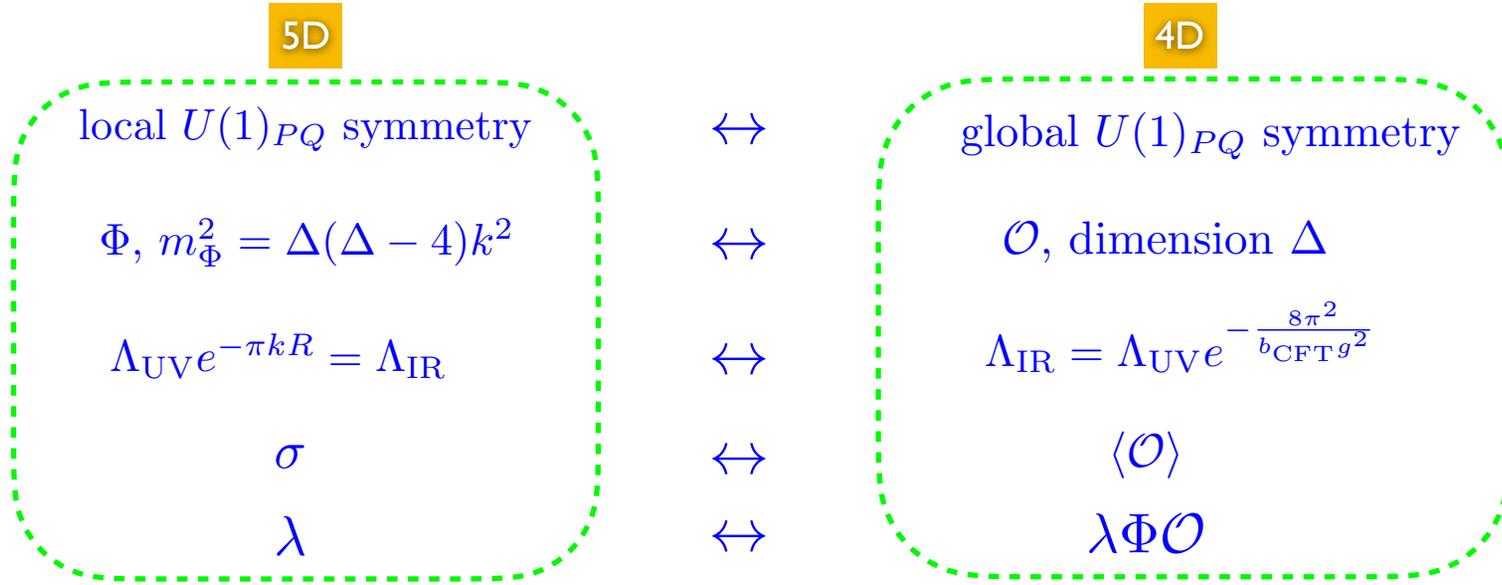
$$10^9 \text{ GeV} \lesssim F_a \lesssim 10^{12} \text{ GeV}$$



$$\Delta_c \gtrsim 10$$

Solves axion-quality problem!

AdS/CFT dictionary



Holographic interpretation:

5D axion,
local U(1) PQ symmetry



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

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

Examples: [Kim 1985; Choi, Kim 1985]; [Randall 1992]; [Redi, Sato 2016]; [Lillard, Tait: 1811.03089]; [Gavela, Ibe, Quilez, Yanagida: 1812.08174]

4D Model

[Gavela, Ibe, Quilez, Yanagida:1812.08174] [Cox, TG, Paul: 2310.08557]

	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)

→ $\mathcal{L}_{PQ} = \frac{c_{PQ}}{4\pi} \frac{(\Lambda_5 f_{PQ}^2)^3}{M_{Pl}^5} e^{-2i \frac{a}{f_{PQ}}} + \text{h.c.}$ composite axion! $f_{PQ} = \Lambda_5/g_*$, $1 \lesssim g_* \lesssim 4\pi$.

Composite sterile neutrinos: $\Psi_1 \equiv \psi_5^\dagger \psi_5^\dagger \psi_{10}^\dagger$, $\Psi_2 \equiv \psi_5^\dagger \psi_{10} \psi_{10}$

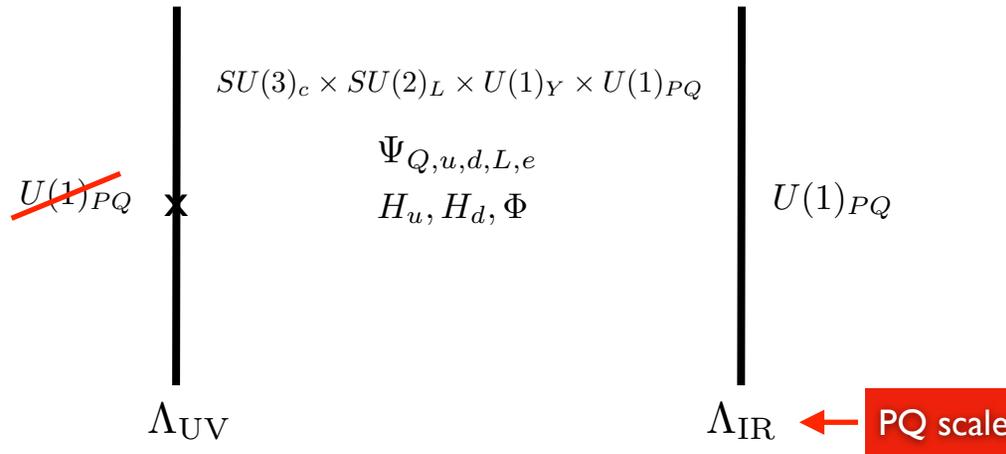
$\mathcal{L}_{\text{EFT}} = \frac{\tilde{\xi}_{ij}}{\Lambda_L^3} L_i H (\psi_5 \psi_5 \psi_{10})_j + \frac{\tilde{\xi}'_{ij}}{\Lambda_L^3} L_i H (\psi_5 \psi_{10}^\dagger \psi_{10}^\dagger)_j + \text{h.c.}$ → $m_{\nu,i}^{\text{active}} = \lambda_{\nu,i} \left(\frac{\Lambda_5 f_{PQ}^2}{\Lambda_L^3} \right)^2 \frac{v^2}{2\Lambda_5}$

Common origin for the see-saw mass scale and the PQ scale! $\frac{m_{\nu,i}^{\text{active}}}{m_a} \sim \frac{\lambda_{\nu,i}}{\mathcal{N} g_*^5} \left(\frac{13.2 \Lambda_5}{\Lambda_L} \right)^6$
i.e. $m_{\nu,i}^{\text{active}} \sim m_a$

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

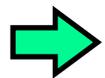
DFSZ-like axion model with bulk Standard Model fermions:

[Also Wilczek 1982; Ema, Hamaguchi, Moroi, Nakayama 2016
Calibbi, Goertz, Redigolo, Ziegler, Zupan 2016; Bonnefoy, Dudas, Pokorski 2019]



Axion-fermion couplings:

$$i \int d^4x \frac{\partial_\mu a^0}{2F_a} (\bar{u}_i \gamma^\mu ((c_u^V)_{ij} - (c_u^A)_{ij} \gamma^5) u_j) \quad A_L^u m_u^{ij} A_R^{u\dagger} = m_{u_i} \quad (\text{similarly for down-type quarks and leptons})$$



Overlap between axion and fermion profiles

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

Numerical results

Flavor-violating couplings:

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

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

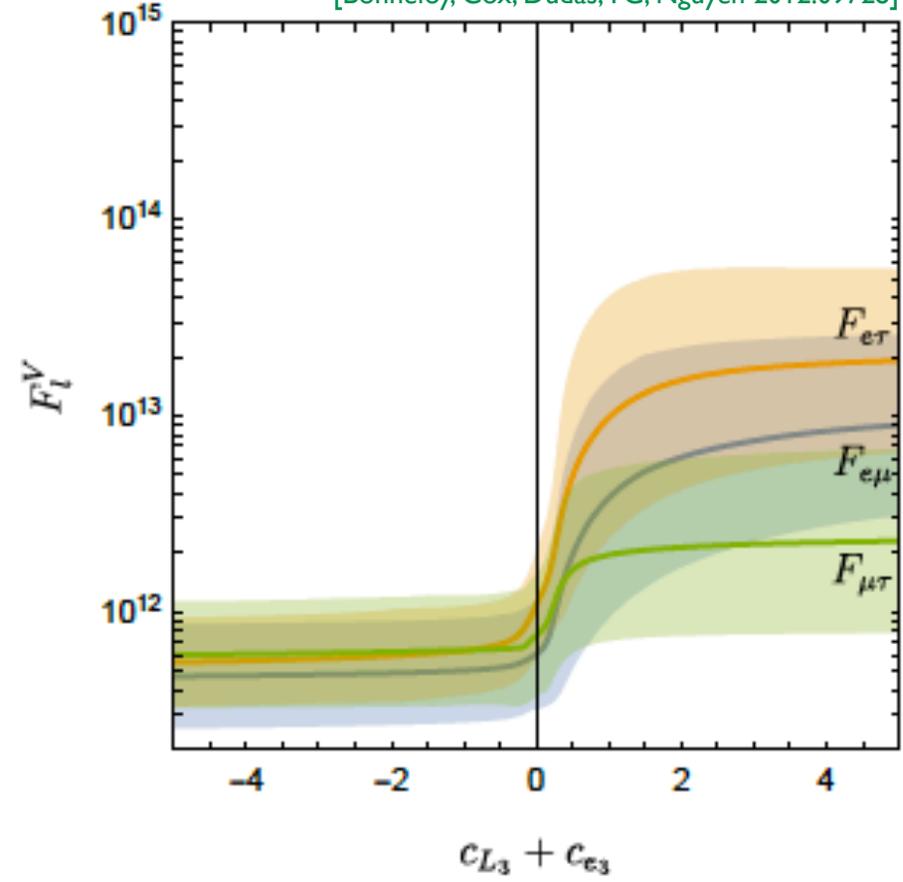
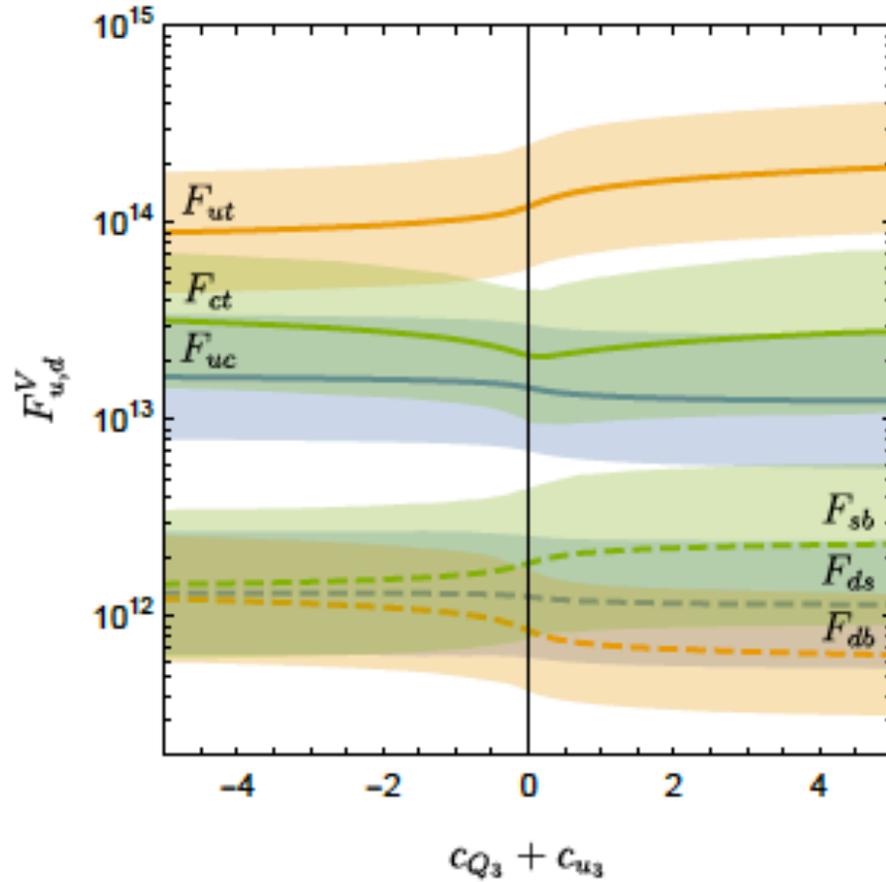
$$kz_{\text{IR}} = 10^{10}, g_5^2 k = 1.$$

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

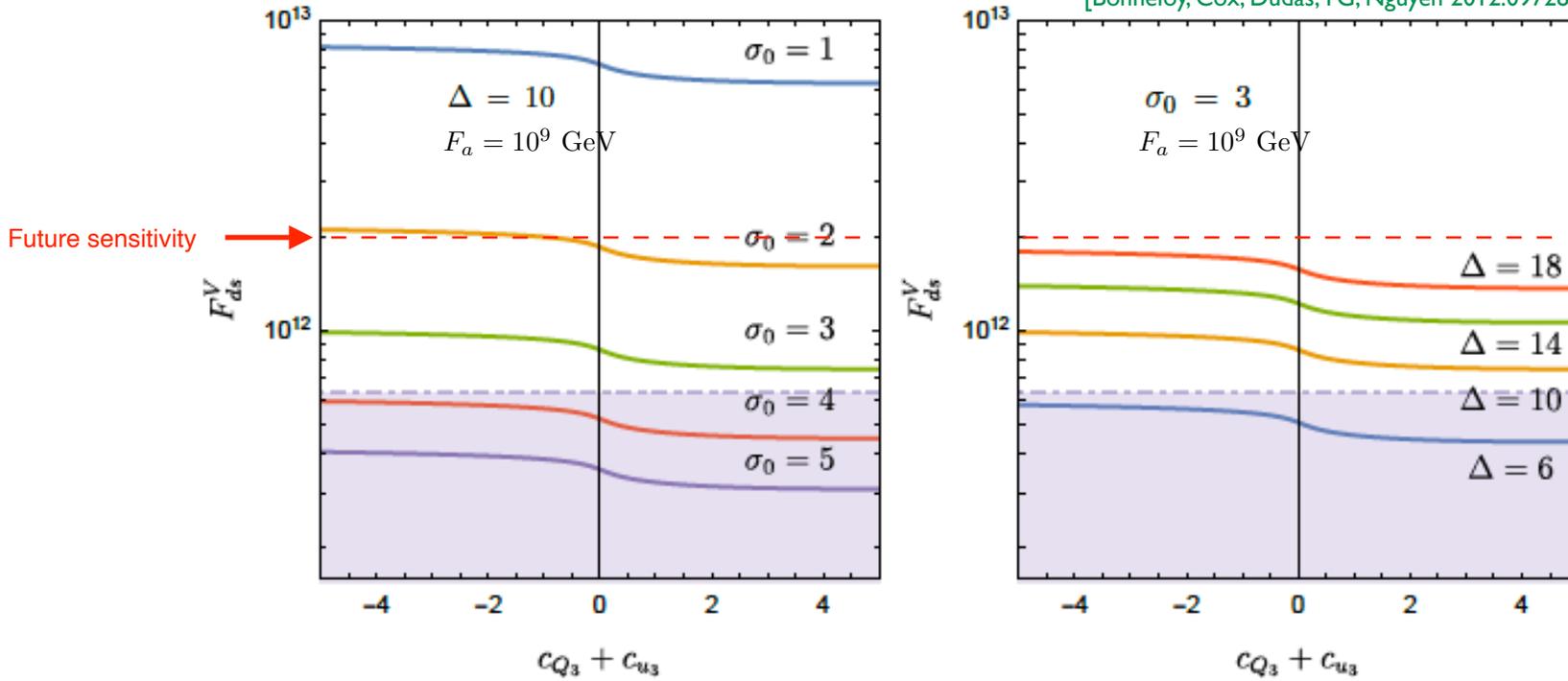
$$F_a \simeq 10^9 \text{ GeV}.$$

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

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



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



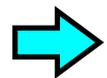
Experimental limits :

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

$$(F_d^V)_{12} \gtrsim 6.8 \times 10^{11} \text{ GeV}$$

($K^+ \rightarrow \pi^+ a$ decays)

[$(8.3 \times 10^{11} \text{ GeV})$ Bauer, Neubert, Renner,
Schnubel, Thamm 2102.13112; 2110.10698]



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

2. Axion mass from 5D small instantons

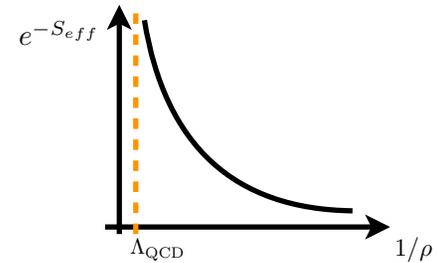
[TG, Khoze, Pomarol, Shirman: 2001.05610]

QCD axion mass:

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

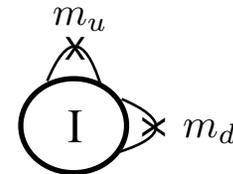
Dilute instanton gas approximation:

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



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

Fermion zero modes: $(\rho m_f)^{N_f} \rightarrow$ suppression $\frac{\prod_f m_f}{\Lambda_{QCD}^{N_f}}$

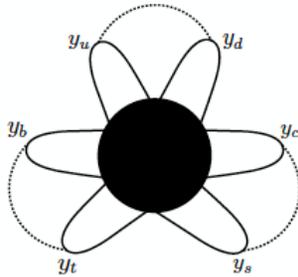


$$\rightarrow \boxed{m_{a,QCD}^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}}$$

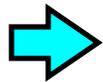
How to enhance QCD axion mass?

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

- Close fermion loops with Higgs boson



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



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

new contribution

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

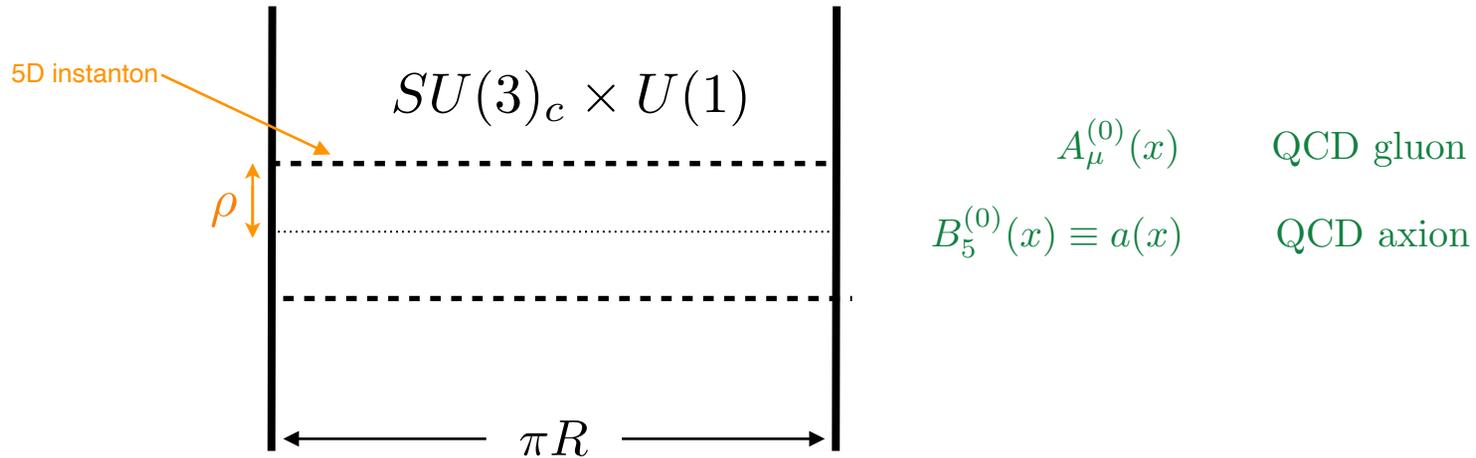
Use 5th dimension to make QCD axion heavy!

QCD in 5D

Flat space 5D metric:

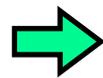
$$ds^2 = dx^2 + dy^2$$

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



5D instanton:

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



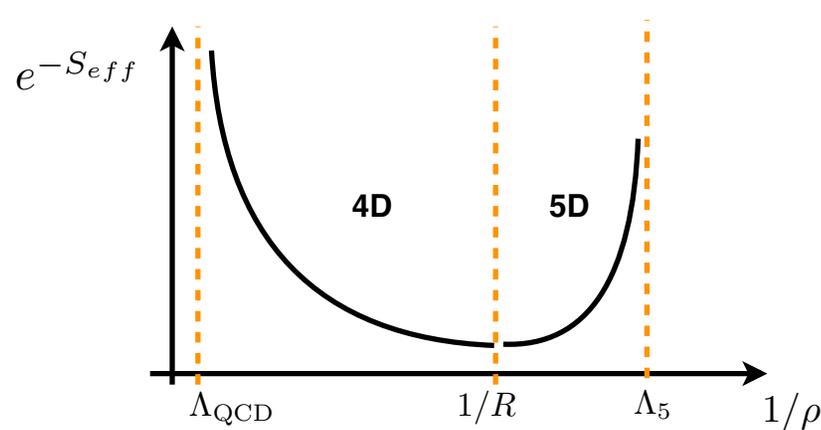
$$S_5^{(I)} = \frac{8\pi^3 R}{g_5^2} = \frac{2\pi}{\alpha_s}$$

Finite action

5D small instantons

[Poppitz, Shirman '02] [TG, Khoze, Pomarol, Shirman: 2001.05610]

Fluctuations + Kaluza-Klein contributions



small instantons!

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



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

power law term!

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

$$R/\rho \gtrsim 20$$

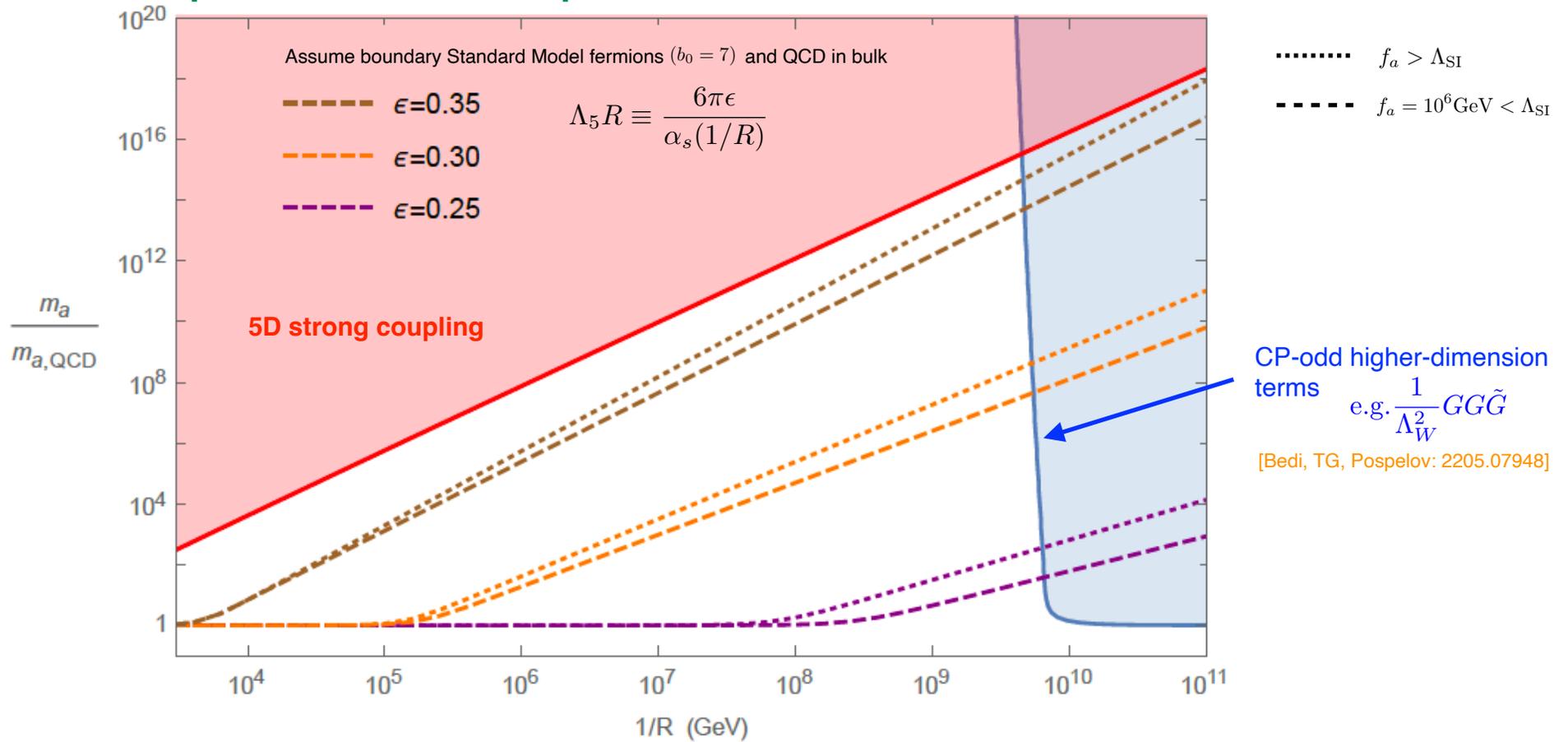


$$K \simeq C[3] \left(\frac{2\pi}{\alpha_s(1/R)} \right)^6 (\Lambda_5 R)^{3-b_0} e^{-\frac{2\pi}{\alpha_s(1/R)} + \Lambda_5 R}$$

power law contribution can overcome suppression

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

[TG, Khoze, Pomarol, Shirman: 2001.05610]



➡ 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:

$$\mathcal{L} \supset \frac{1}{\Lambda_W^2} GG\tilde{G}$$

[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]

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

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

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

Neutron EDM:

$$|\theta_{\text{ind}}| \lesssim 10^{-10}$$



$$\frac{\Lambda_{\text{SI}}}{\Lambda_W} \lesssim 10^{-6}$$

What is the Holographic View?

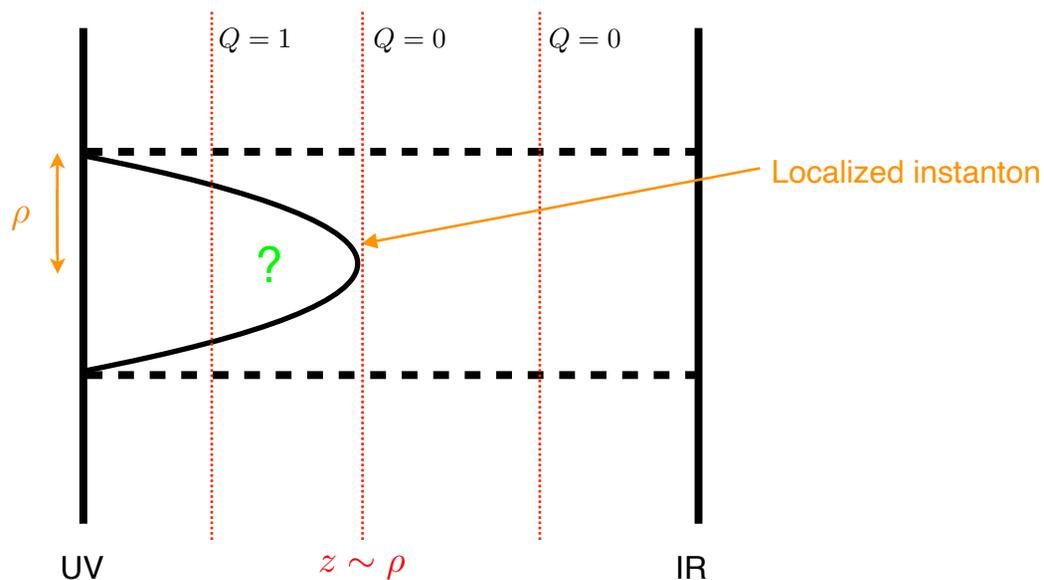
[TG, Pomarol: 2110.01762]

Running coupling:

$$\frac{1}{g_4^2(\mu)} = \frac{1}{g_4^2} - \frac{L}{g_5^2} \log(\mu z_{UV})$$

Topological charge:

$$Q = \frac{1}{32\pi^2} \int d^4x G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$



Axion mass: $m_a^2 f_a^2 \propto \int \frac{d\rho}{\rho^5} e^{-S}$



$$S_{\text{local}} = \frac{8\pi^2}{g_4^2(1/\rho)} \ll \frac{8\pi^2}{g_4^2(z_{IR}^{-1})}$$



Larger axion mass enhancement compared to flat space?

However, topological charge conservation

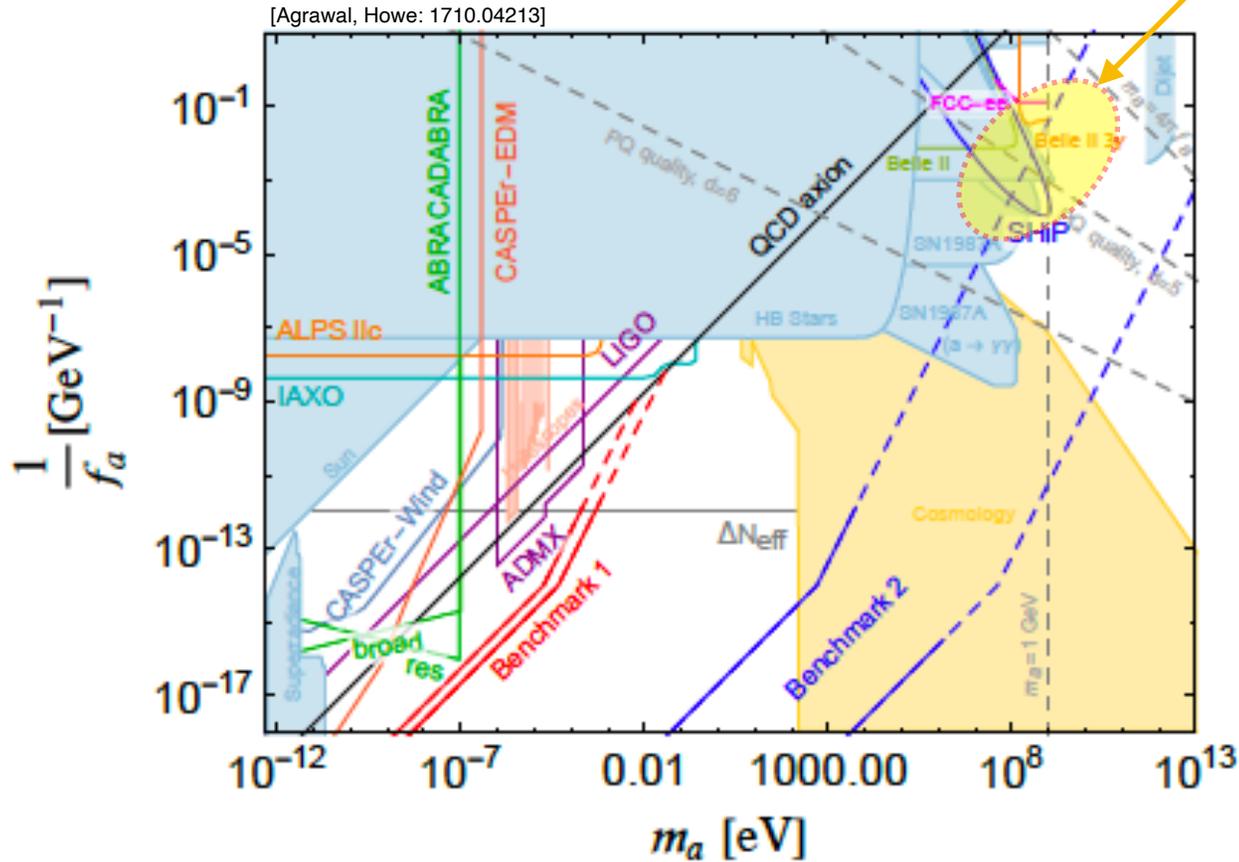


NO localized instanton!



CFT dual *necessarily* contains colored fermions!

Heavy Axion Limits



Favoured by axiogenesis!

[Co, TG, Harigaya, 2206.00678]



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]

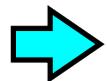
[Valenti, Vecchi, Xu: 2206.04077]

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

[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]
[Dunsky, Hall, Harigaya: 2302.04274]



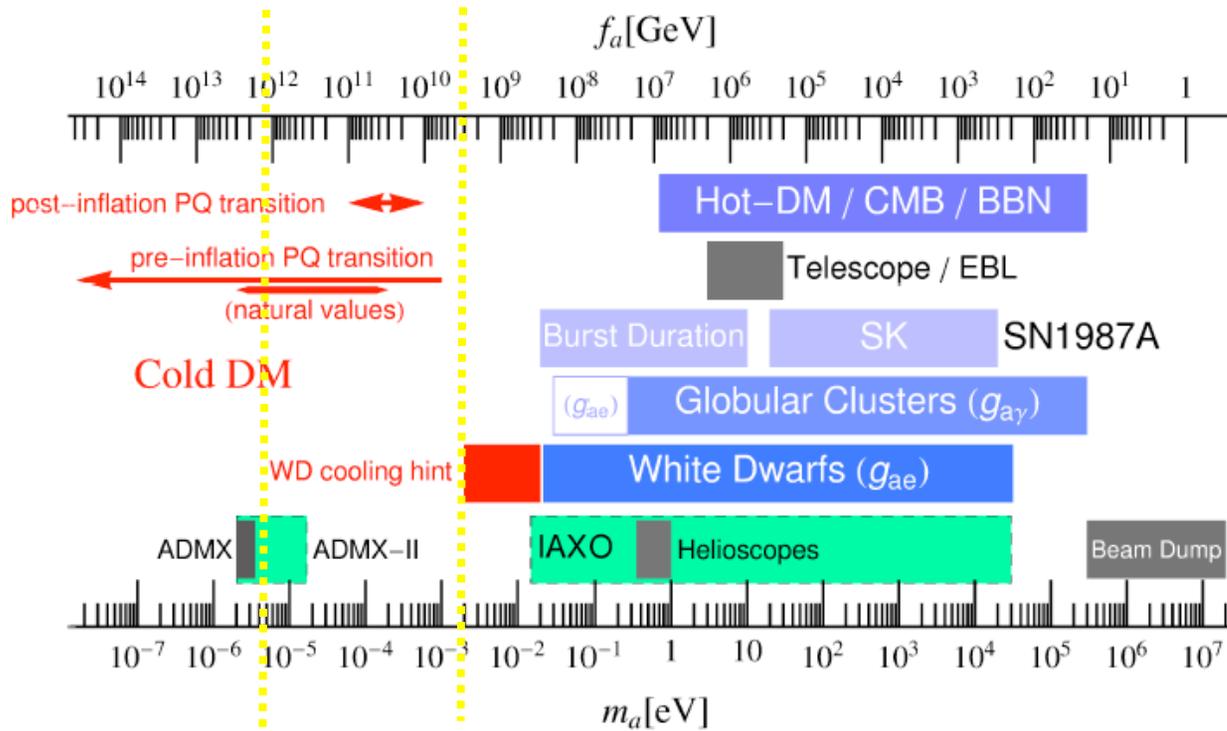
Axion mass is sensitive to UV completion!

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!*
- Holographic view provides *complete* framework to study QCD axion!

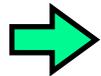
Extra Slides

QCD axion limits



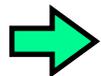
$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}$$

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



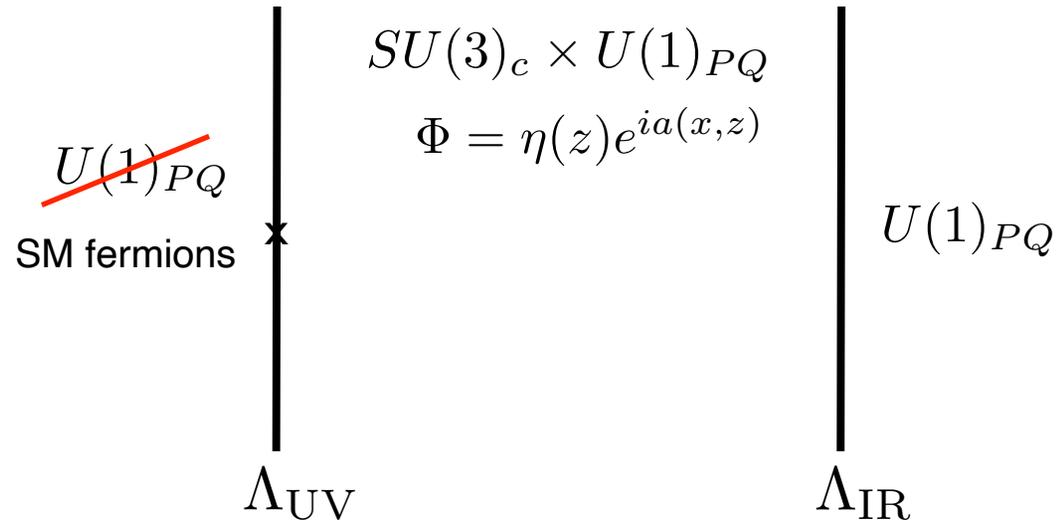
axion weakly-coupled - “invisible”

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



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

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: $V_M \rightarrow V_M + \partial_M \alpha$

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

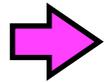
Add IR boundary term:

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

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

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

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

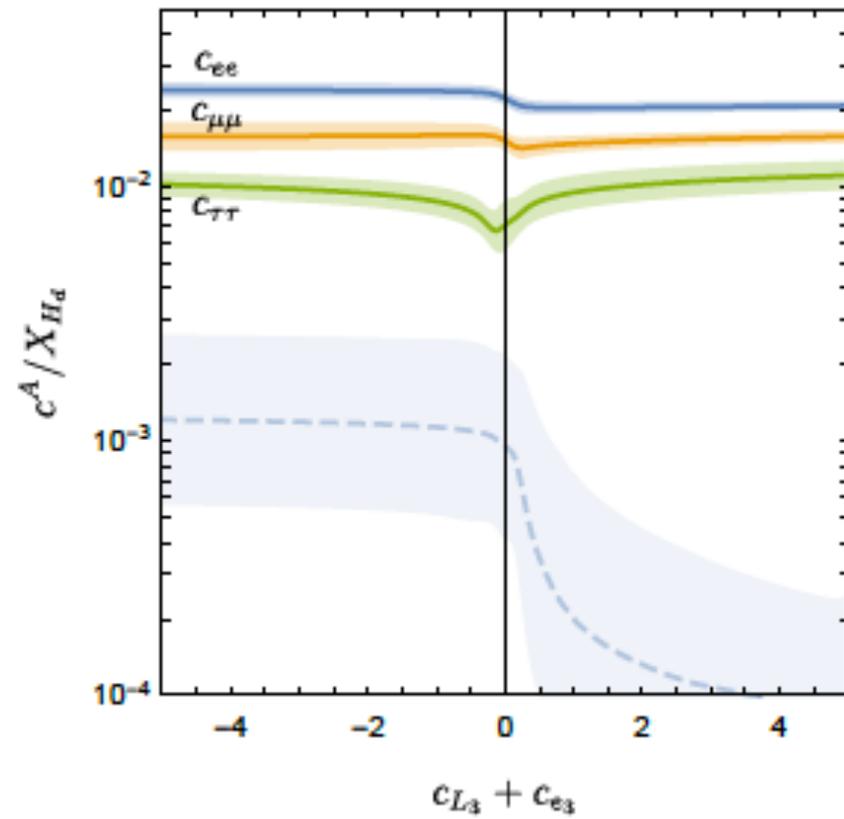
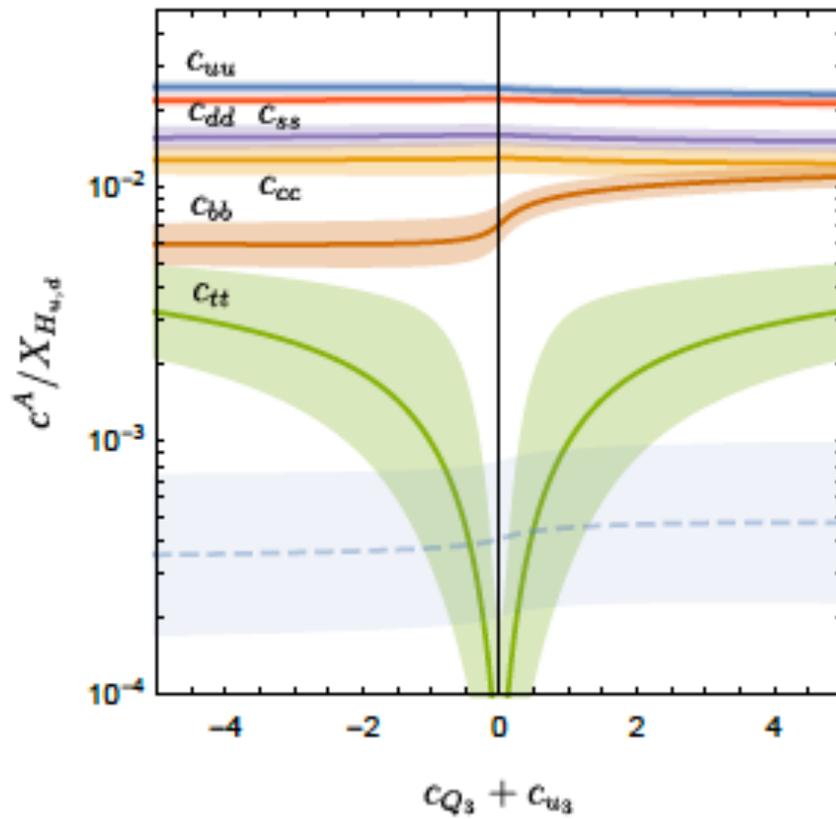
$$\Delta = 10 \quad \sigma_0 = 3.$$

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

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

Flavor-preserving couplings:

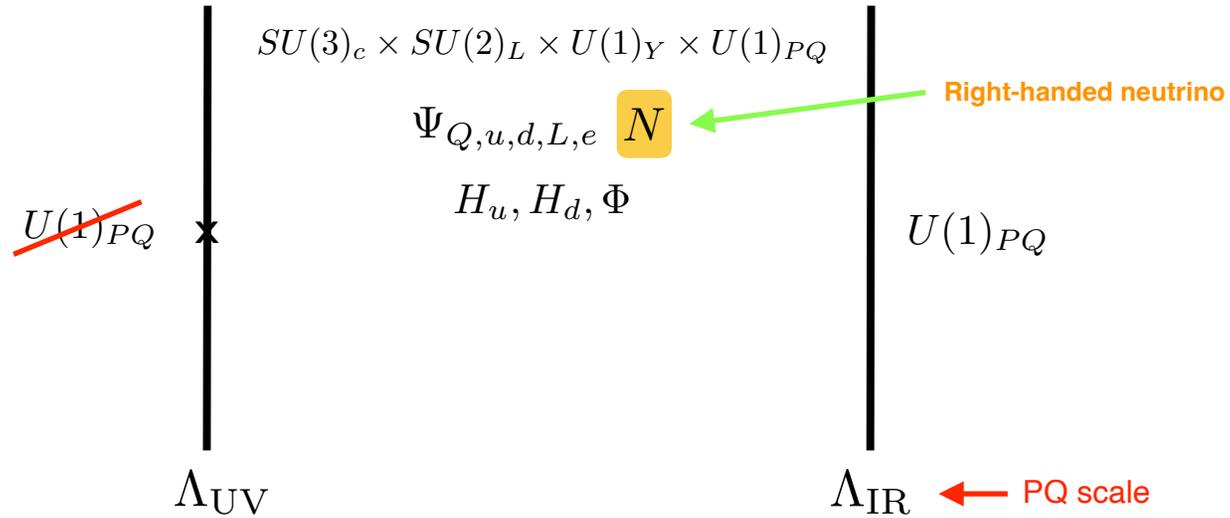
[Bonnefoy, Cox, Dudas, TG, Nguyen 2012.09728]



Neutrino-Axion Model

[Cox, TG, Nguyen: 2107.14018]

[Also Mohapatra, Senjanovic 1983; Holman, Lazarides, Shafi 1983; Langacker, Peccei, Yanagida 1986; Bertolini et al 2015; Clarke, Volkas 2016]



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:

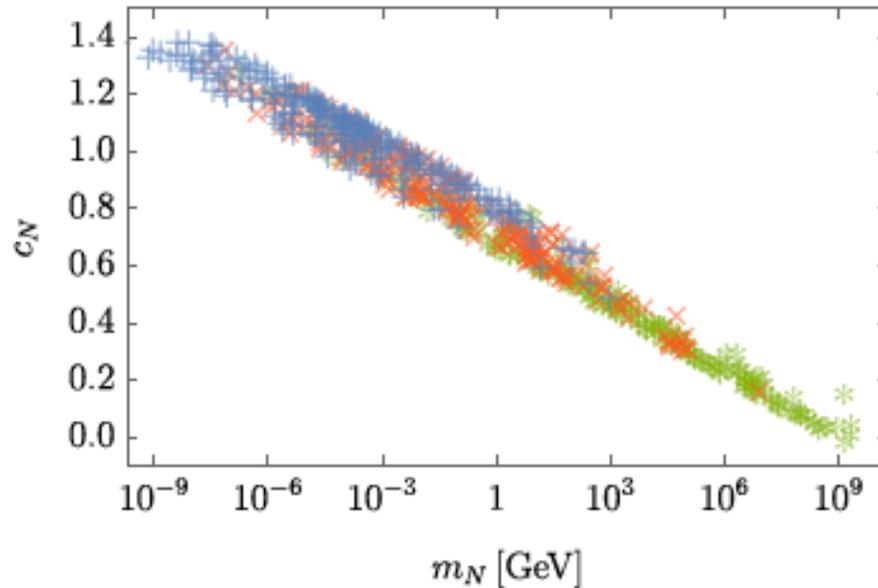
$$\frac{1}{2} \left(b_{N,ij} N_i^c N_j + \frac{y_{N,ij}^{(5)}}{k^{3/2}} \Phi N_i^c N_j + \text{h.c.} \right)$$

Predictions:

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

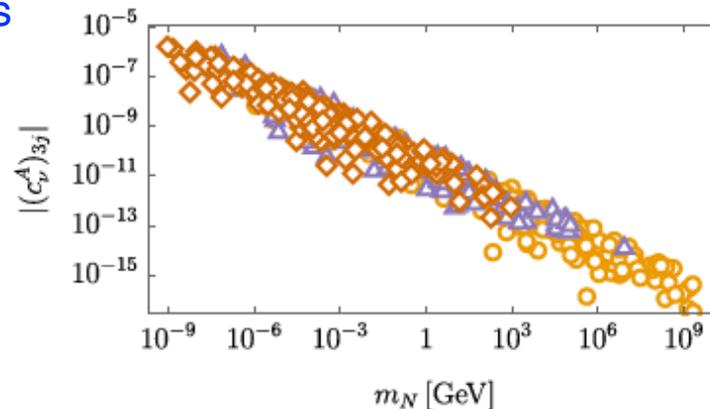
$$\sigma_0 = 0.1, \lambda = 0.1, \Delta = 10, \tan \beta = 3, k_{ZIR} = 10^7 \quad \Rightarrow \quad F_a \simeq 8.12 \times 10^9 \text{ GeV}$$

◆ Light sterile neutrinos!



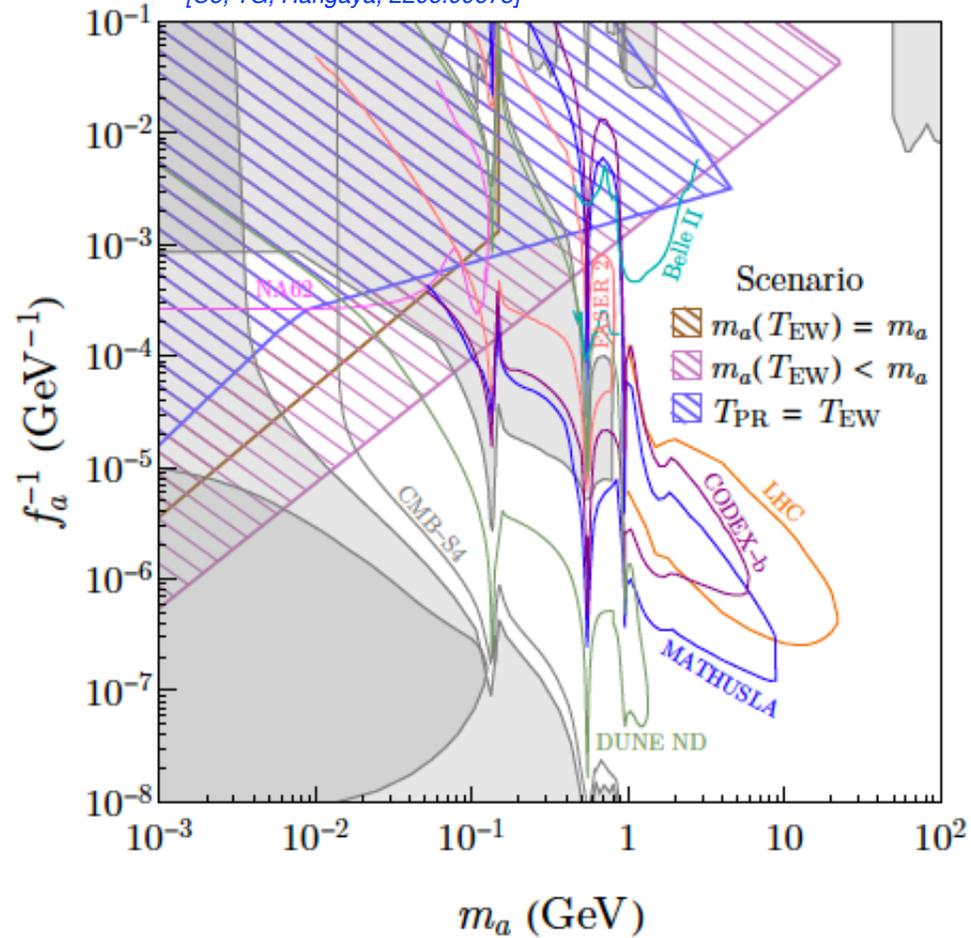
$$\Rightarrow 1 \text{ eV} \lesssim m_N \lesssim 10^9 \text{ GeV}$$

◆ Axion-neutrino couplings



\Rightarrow Probe local DM halo with neutrino oscillations **NEW**
[TG, Shkerin: 2305.06441]

[Co, TG, Harigaya, 2206.00678]



Heavy QCD axion solves strong CP + baryon asymmetry!