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

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

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

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

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

Dynamical Solution: PQ mechanism and axion

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

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

dim 5 term; diphoton coupling; axial current coupling

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

⇨ $m_a^2 f_a^2 \sim \frac{1}{8}\Lambda^4_{\rm QCD}$ [or precisely, $m_a = 5.70(7)\ \mu\mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$]

light-quark contribution

[Cortona, Hardy, Pardy Vega, Villadoro, 1511.02867]

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

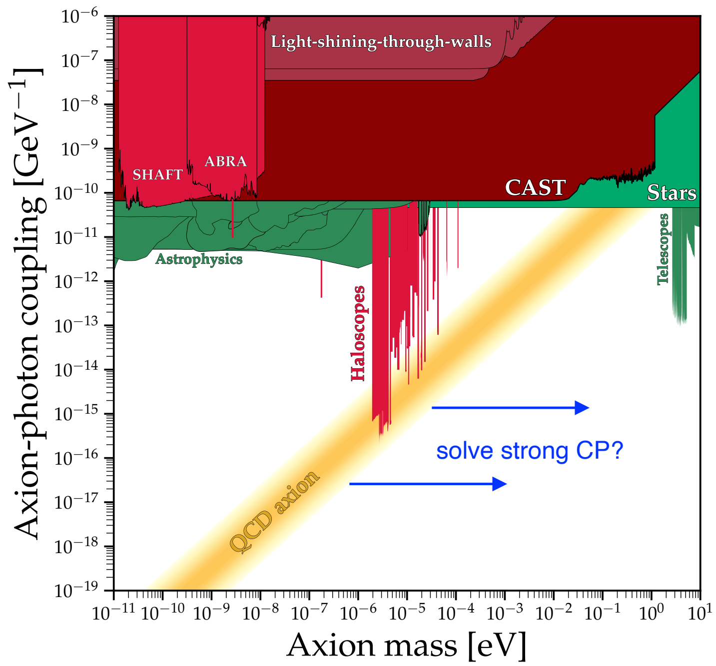
Terms must be suppressed to very high order! $(c_n \sim 1, n \geq 10)$

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

Questions

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

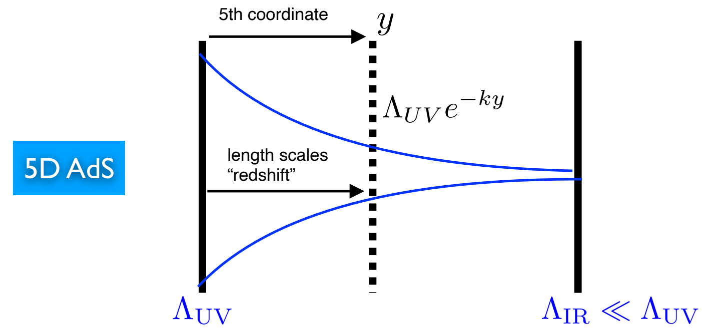
$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}$$



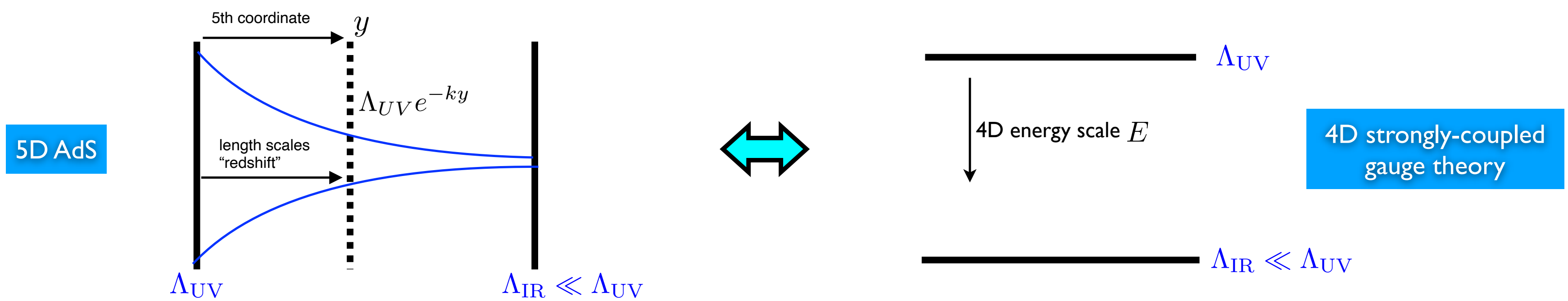
⇨ Use 5th dimension to address these questions!

Why use the 5th dimension?

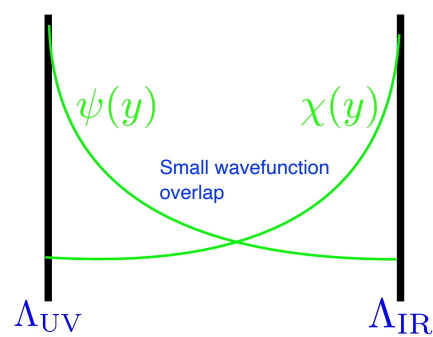
◆ Can generate a hierarchy of scales!



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



◆ Can generate small couplings!

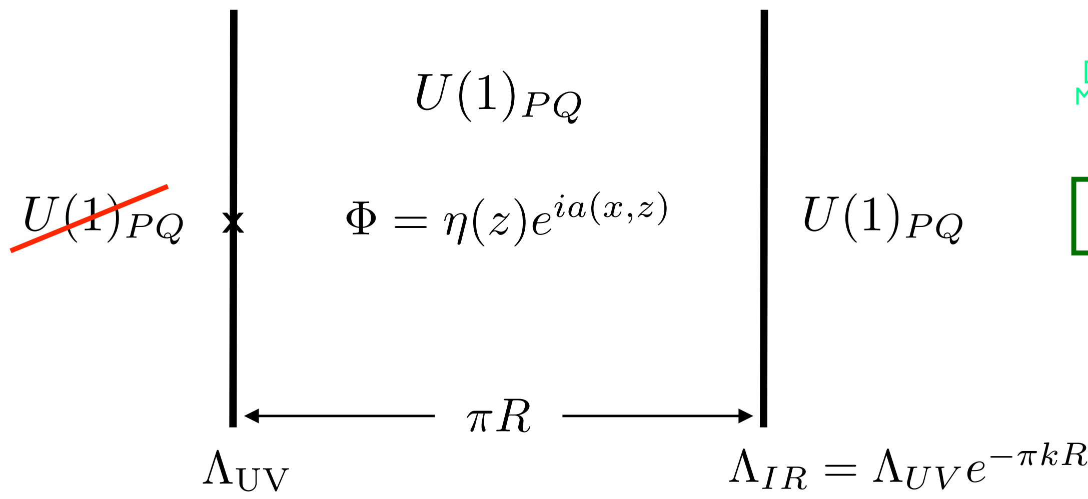


I. Axion Quality Problem [Cox, TG, Nguyen 1911.09385]

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

AdS curvature scale

"slice of AdS"



[Randall, Sundrum 1999]
[Dienes, Dudas, TG 1999]
[Choi 2003; Flacke, Gripaios, March-Russell, Maybury 2006]

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

"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

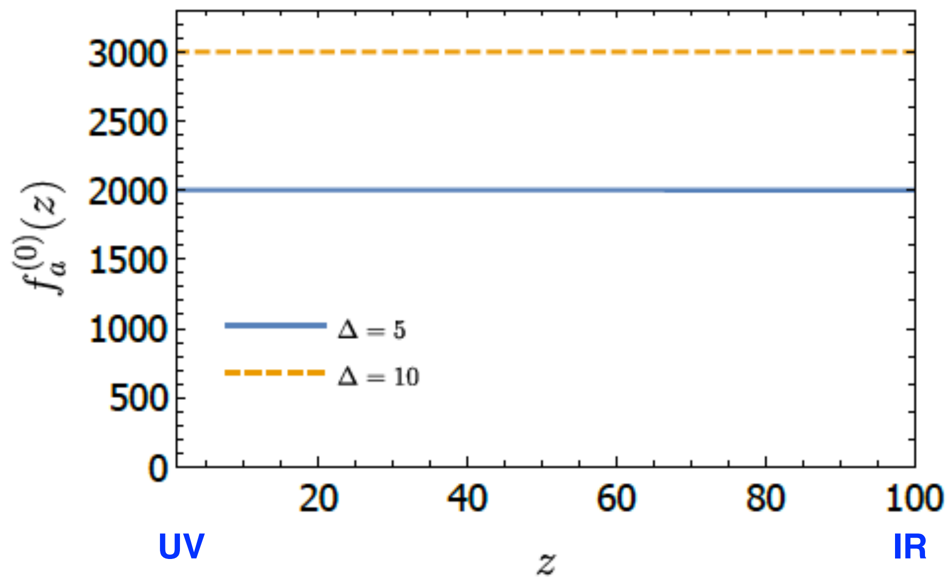
$$\sigma = \sqrt{v_{IR}^2 - \frac{\Delta}{2\lambda_{IR}}}(kz_{IR})^{-\Delta} \equiv \sigma_0\,(kz_{IR})^{-\Delta}$$

"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:

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

Massless axion

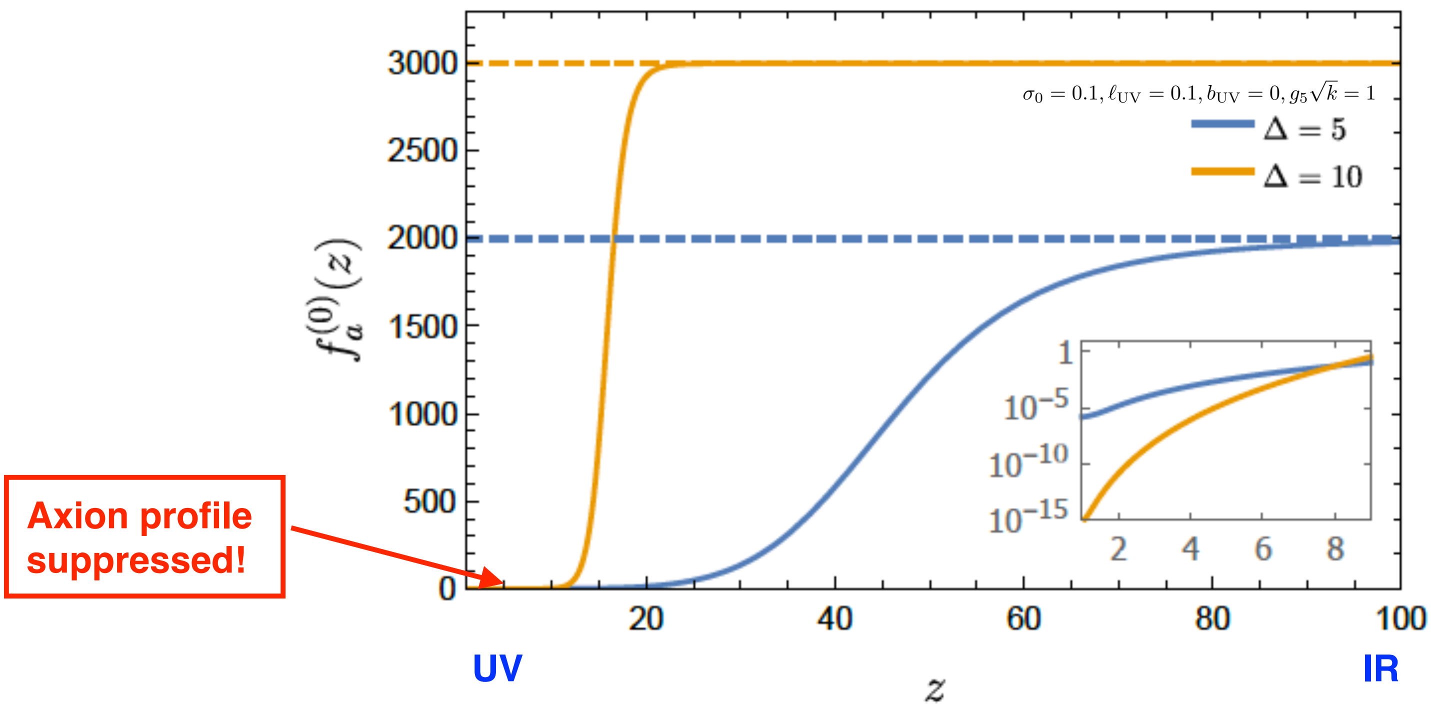
UV PQ-breaking $(\lambda \neq 0)$

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

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

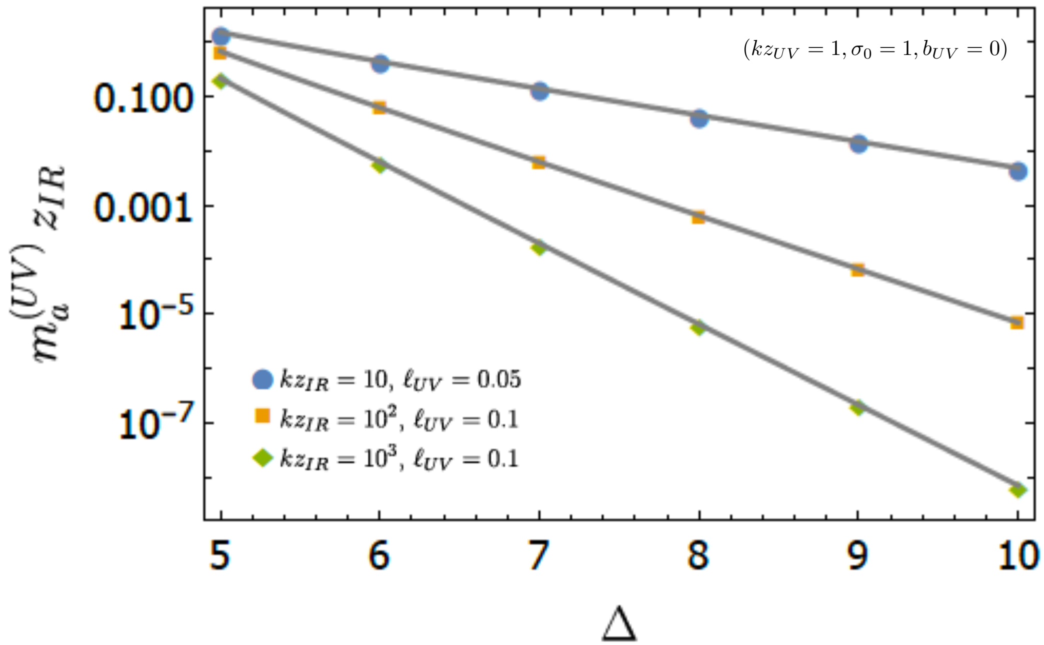
$$f_a^{(0)}(z) \simeq z_{IR}\frac{k^{3/2}}{\eta(z)}\sqrt{\Delta - 1}\left(\frac{z}{z_{IR}}\right)^{\Delta}\left[1 + \frac{2\lambda(\Delta-2)(kz_{UV})^{\Delta}(kz)^{2(2-\Delta)}}{\ell_{UV} + 2\sigma_0(\Delta-2)(z_{UV}/z_{IR})^{\Delta}}\right]$$

[Cox, TG, Nguyen 1911.09385]



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

[Cox, TG, Nguyen 1911.09385]



UV axion mass *suppressed* for large Δ

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

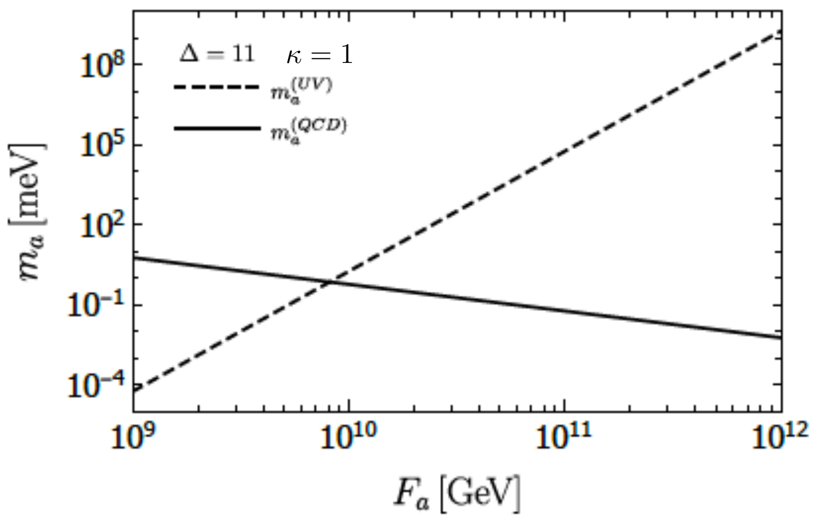
UV explicit PQ violation

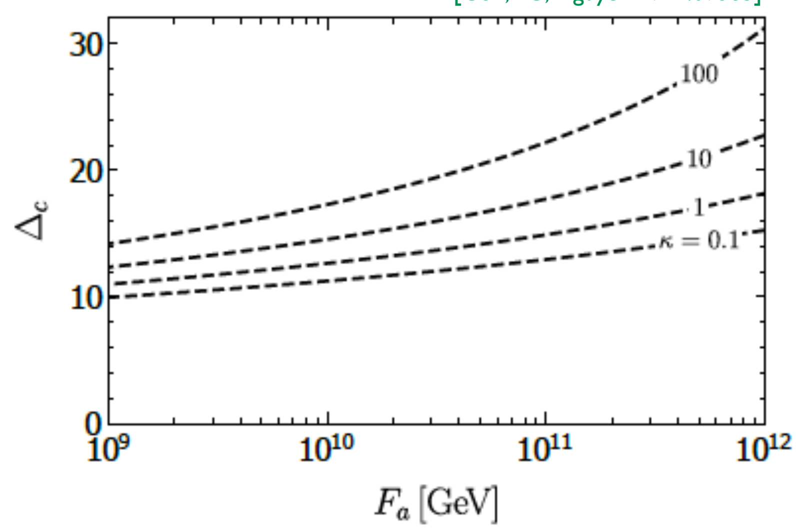
$$V(a^{(0)}) \simeq -(m_a^{(QCD)})^2 F_a^2 \cos\left(\frac{a^{(0)}}{F_a} + \bar{\theta}\right) - (m_a^{(UV)})^2 F_a^2 \cos\left(\frac{a^{(0)}}{F_a} + \delta\right)$$

relative phase

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

[Cox, TG, Nguyen 1911.09385]





$10^9\ \text{GeV} \lesssim F_a \lesssim 10^{12}\ \text{GeV}$ ⇒ $\Delta_c \gtrsim 10$ ← **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	$\leftrightarrow$	$\lambda\Phi\mathcal{O}$

Holographic interpretation:

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

Axion quality: $\frac{c_n}{M_P^{n-4}}\Phi^n \quad (n \gtrsim 10) \quad \leftrightarrow \quad \frac{c_\Delta}{M_P^{\Delta-4}}\mathcal{O} \sim \frac{c_\Delta}{M_P^{\Delta-4}}(\underbrace{\psi_i\psi_j\ldots\ldots\psi_k}) \quad (\Delta \gtrsim 10)$

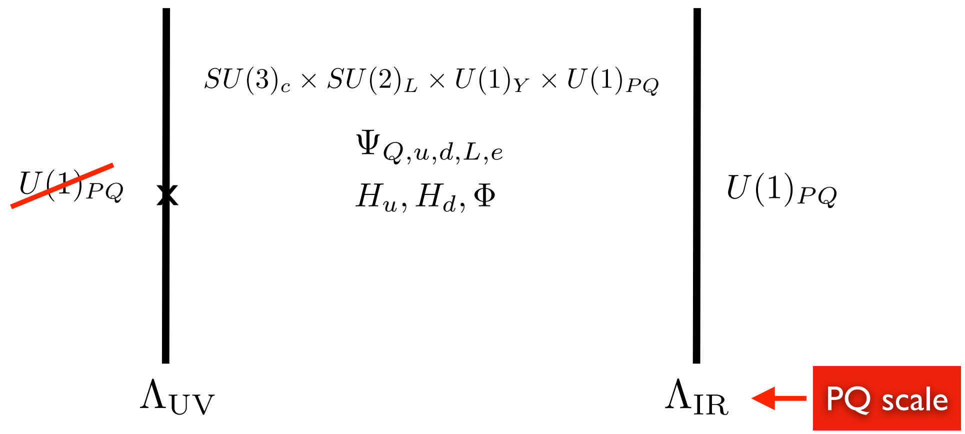
due to gauge + Lorentz symmetry!

Examples: [Kim 1985; Choi, Kim 1985];
[Randall1992]; [Redi, Sato 2016]; [Lillard, Tait: 1811.03089]; [Gavela, Ibe, Quilez, Yanagida: 1812.08174]

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:

$$i\int d^4x \frac{\partial_\mu a^0}{2F_a}\left(\bar{u}_i\gamma^\mu\left((c_u^V)_{ij} - (c_u^A)_{ij}\gamma^5\right)u_j\right) \qquad A_L^u m_u^{ij} A_R^{u\dagger} = m_{u_i}$$

(similarly for down-type quarks and leptons)

Overlap between axion and fermion profiles

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

Numerical results

Flavor-violating couplings:

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

$F^A_{u,d,\ell} \approx \mathcal{O}(F^V_{u,d,\ell})$

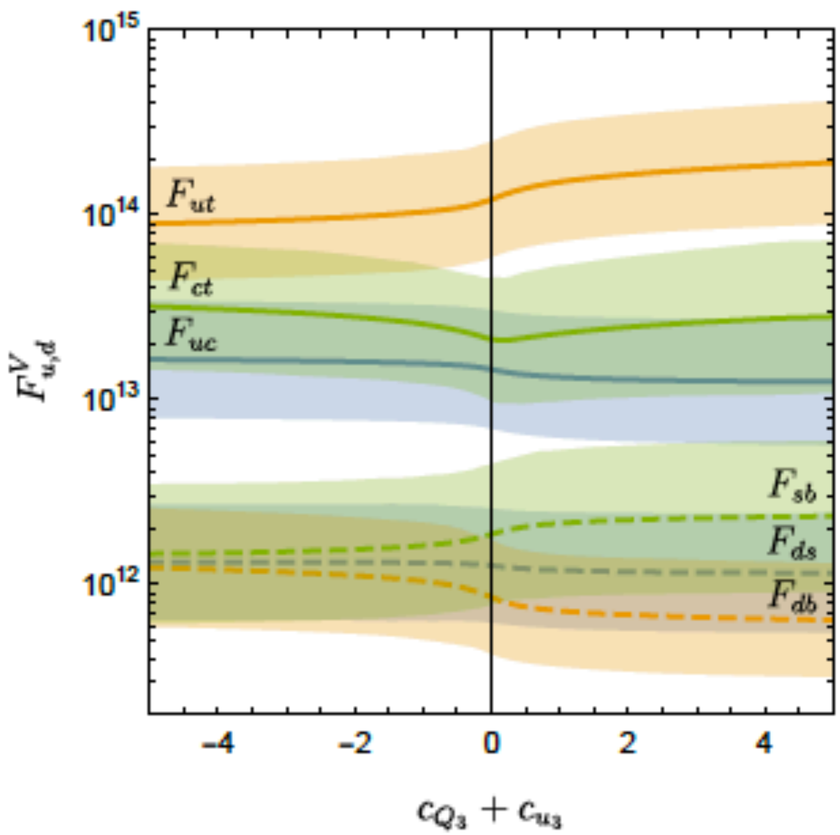
$kz_{\rm IR} = 10^{10}, g_5^2 k = 1$

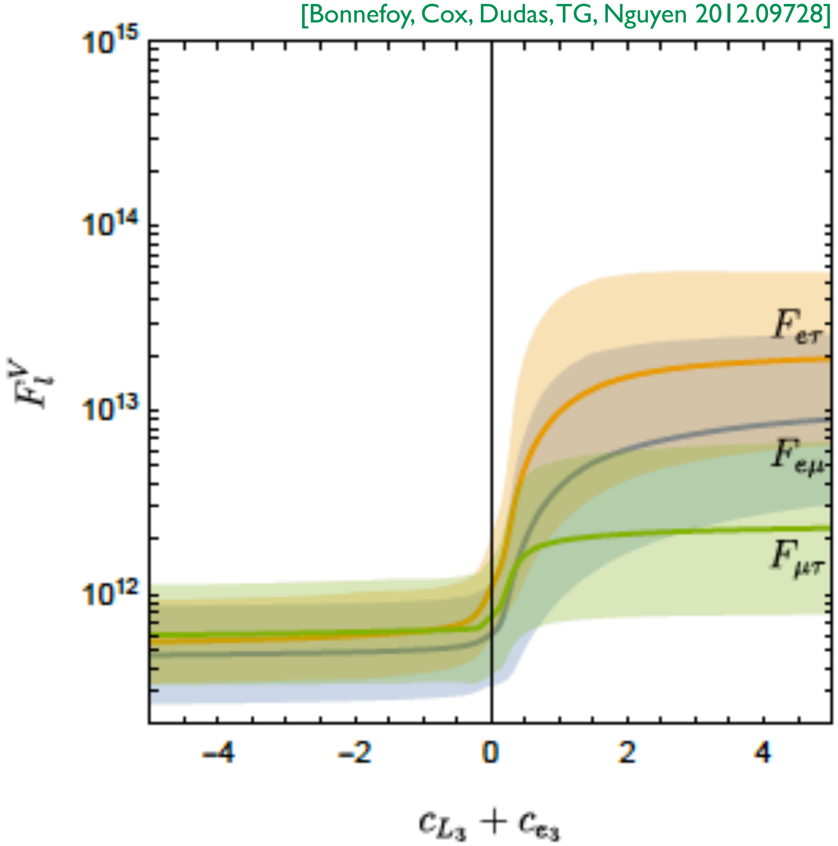
$\Delta = 10 \quad \sigma_0 = 3$

$F_a \simeq 10^9$ GeV.

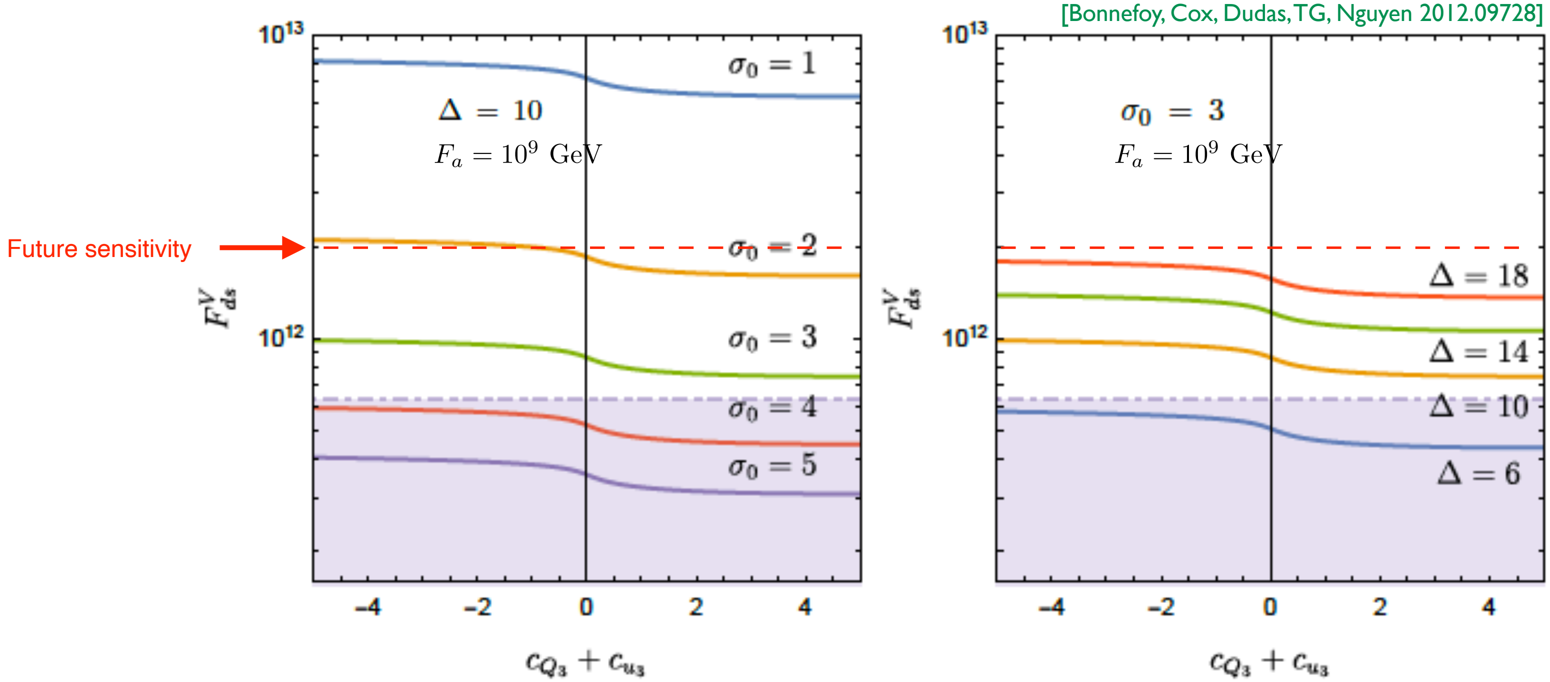
Scan over $y^{(5)}_{u,d,e} \sim 1$

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





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



Experimental limits : $(F^V_d)_{12} \gtrsim 6.8 \times 10^{11}$ GeV $(K^+ \to \pi^+ a$ decays)

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

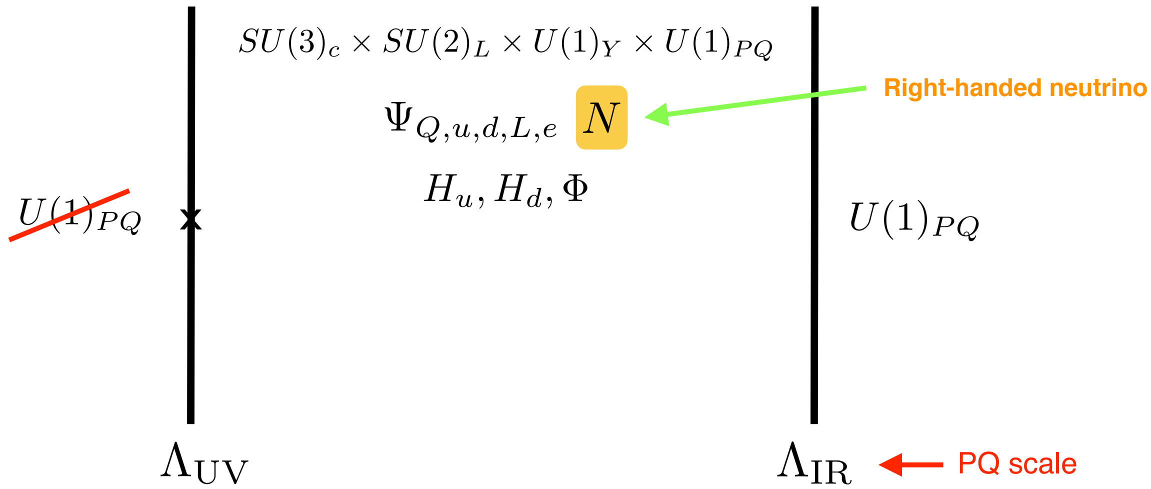
[$(8.3 \times 10^{11}$ GeV) Bauer, Neubert, Renner, Schnubel, Thamm 2102.13112; 2110.10698]

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

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: $$\frac{1}{\sqrt{k}}\left(y^{(5)}_{\nu,ij}\overline{L_i}N_j H_u + y^{(5)}_{e,ij}\overline{L_i}E_j H_d + \text{h.c.}\right)$$ ← PQ charge of N forbids bulk Majorana terms

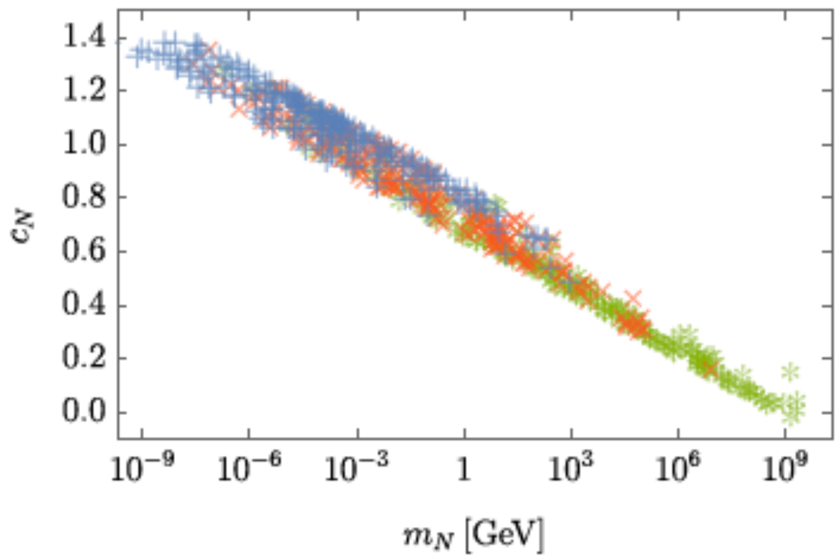
UV boundary: $$\frac{1}{2}\left(b_{N,ij}\overline{N^c_i}N_j + \frac{y^{(5)}_{N,ij}}{k^{3/2}}\Phi\overline{N^c_i}N_j + \text{h.c.}\right)$$

Predictions:

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

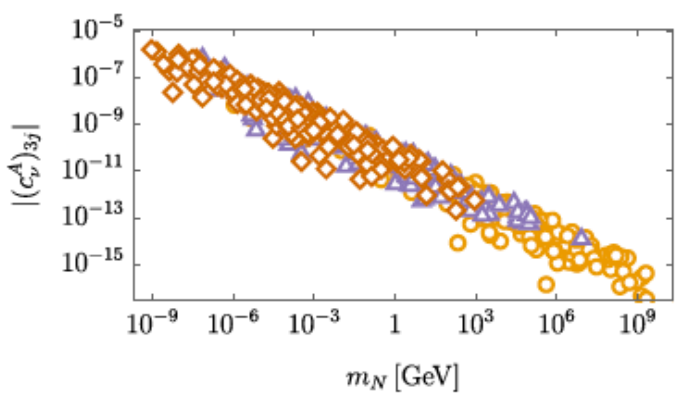
$\sigma_0 = 0.1, \lambda = 0.1, \Delta = 10, \tan\beta = 3, kz_{IR} = 10^7$ ⇨ $F_a \simeq 8.12 \times 10^9$ GeV

✦ Light sterile neutrinos!



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

✦ Axion-neutrino couplings



⇨ Probe local DM halo with neutrino oscillations NEW
[TG, Shkerin: 2305.06441]

Local Dark Matter Halo [TG, Shkerin: 2305.06441]

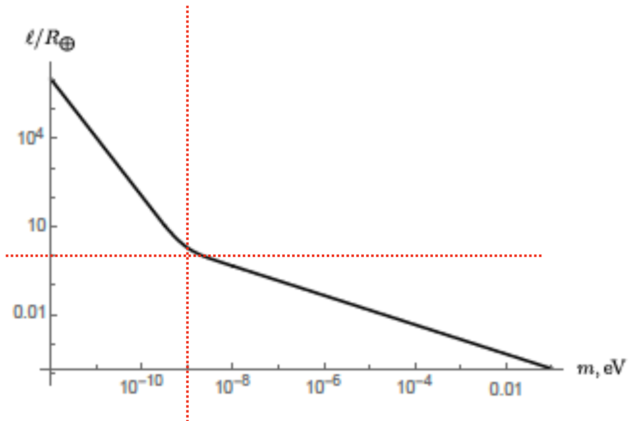
Ultra-light particles (e.g. axion) = dark matter

➡ can form dense compact objects $\rho_{\text{local}} \gg \rho_{\text{average}}$

Consider a local halo surrounding the Earth:

Nonrelativistic ansatz: $\varphi(r,t) = \sqrt{\frac{2c}{m}}\left(\Psi(r,t)e^{-\imath mc^2 t} + c.c.\right)$ $\quad \Psi(r,t) = \psi(r)e^{-\imath Et}$

$$-\frac{1}{x^2}\frac{\mathrm{d}}{\mathrm{d}x}\left(x^2\frac{\mathrm{d}\psi}{\mathrm{d}x}\right) + 2(\mathcal{M}\bar{\Phi} - \mathcal{E})\psi = 0 \qquad x = r/R\,, \quad \mathcal{M} = Gm^2MR\,, \quad \mathcal{E} = EmR^2$$



HALO SIZE

$$\ell \sim R_\oplus \left(\frac{10^{-9}\,\text{eV}}{m}\right)^2 \qquad m \ll 10^{-9}\,\text{eV}$$

$$\ell \sim R_\oplus \left(\frac{10^{-9}\,\text{eV}}{m}\right)^{1/2} \qquad m \gg 10^{-9}\,\text{eV}$$

How to probe halo? Use neutrino oscillations!

Neutrino evolution (Assume 2 flavour, ultrarelativistic, neglect decoherence and dispersion)

$$i\frac{d\nu_a}{dz} = H_{ab}\nu_b \qquad H = \frac{1}{2E}U_0\mathrm{diag}(0, \Delta m^2_{0,21}, ...)U_0^\dagger + \Delta H$$

Dark matter-neutrino interaction

$$\mathcal{L}_{5,\mathrm{int}} = -\frac{g_{ab}}{\Lambda_5}\partial_\mu\varphi\,\bar{\psi}_{La}\gamma^\mu\psi_{Lb} \quad \Rightarrow \quad \Delta H_5 = \frac{m}{\Lambda_5}g\varphi$$

where $\varphi(r,t) = f(r)\cos(mt+\delta)$
$(\dot{\varphi} \sim m\varphi \gg \nabla\varphi)$

Survival probability

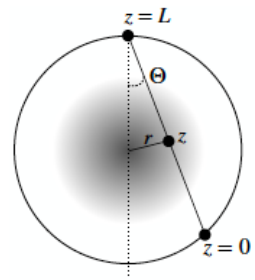
z-dependent eigenvalues affect survival probability!

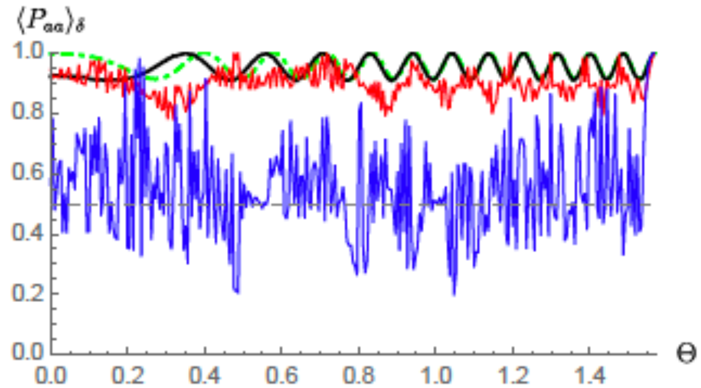
$$P_{ab}(L) = \left|\sum_i U_{ai}(0)e^{-\frac{i}{2E}\int_0^L dz\, m_i^2(z)}U^*_{bi}(L)\right|^2$$

$$\epsilon \equiv \frac{\beta f_0}{m} \sim \left(\frac{\beta}{10^{-22}}\right)\left(\frac{m}{10^{-10}\,\mathrm{eV}}\right)\left(\frac{M_{\mathrm{halo}}}{10^{15}\,\mathrm{kg}}\right)^{1/2}$$
expansion parameter

$$\eta \equiv \frac{mE}{\Delta m_0^2} = \left(\frac{2.5\times10^{-3}\,\mathrm{eV}^2}{\Delta m_0^2}\right)\left(\frac{m}{10^{-10}\,\mathrm{eV}}\right)\left(\frac{E}{25\,\mathrm{MeV}}\right)$$
number of halo oscillations per neutrino oscillation

Small halo $(\ell < R_\oplus)$





$m = 3 \times 10^{-9}$ eV, $E = 1$ GeV

$\Delta m_0^2 \approx 2.5 \times 10^{-3}$ eV, $\sin^2 2\theta_0 \approx 0.087$.

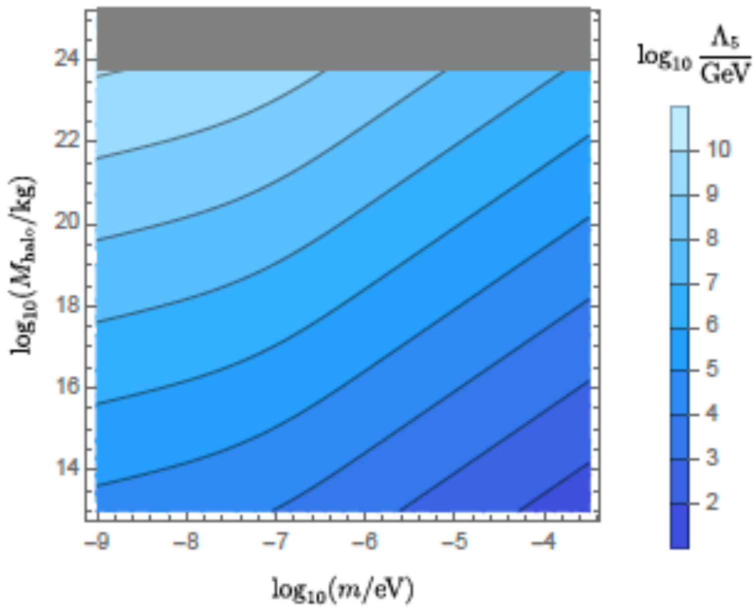
$\epsilon = 0.1$ (black line)

$\epsilon = 0.5$ (thin, red line),

$\epsilon = 2$ (thin, blue line),

$$\epsilon \sim \left(\frac{\beta}{10^{-23}}\right)\left(\frac{10^{-9}\,\mathrm{eV}}{m}\right)^{5/4}\left(\frac{M_{\rm halo}}{10^{15}\,\mathrm{kg}}\right)^{1/2}$$

(10% deviation)



$E = 1\,\mathrm{GeV}$ (atmospheric neutrinos)

$\Delta m_0^2 = 2.5 \times 10^{-3} \mathrm{eV}^2$

$\Theta_{\rm res} = 30^\circ$

$$\eta = 400 \left(\frac{2.5 \times 10^{-3}\,\mathrm{eV}^2}{\Delta m_0^2}\right)\left(\frac{m}{10^{-9}\,\mathrm{eV}}\right)\left(\frac{E}{1\,\mathrm{GeV}}\right)$$

Can probe scales up to $\Lambda_5 \sim 10^{10}$ GeV

2. Axion mass from 5D small instantons

[TG, Khoze, Pomarol, Shirman: 2001.05610]

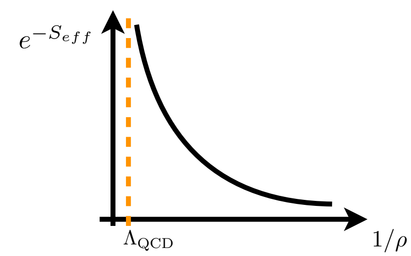
QCD axion mass:

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

"topological susceptibility"

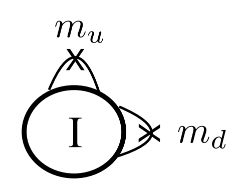
Dilute instanton gas approximation:

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



QCD asymptotically free ⇨ $\mathcal{T} \propto \Lambda^4_{QCD}$ *"Large instantons"* $\rho \sim 1/\Lambda_{QCD}$

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



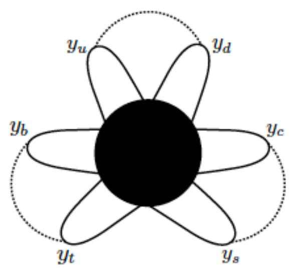
⇨

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

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



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

$$\Rightarrow \quad m_a^2 f_a^2 \sim \frac{1}{8}\Lambda_{\rm QCD}^4 + \Lambda_I^4 \qquad \text{where } \Lambda_I \gg \Lambda_{\rm QCD}$$

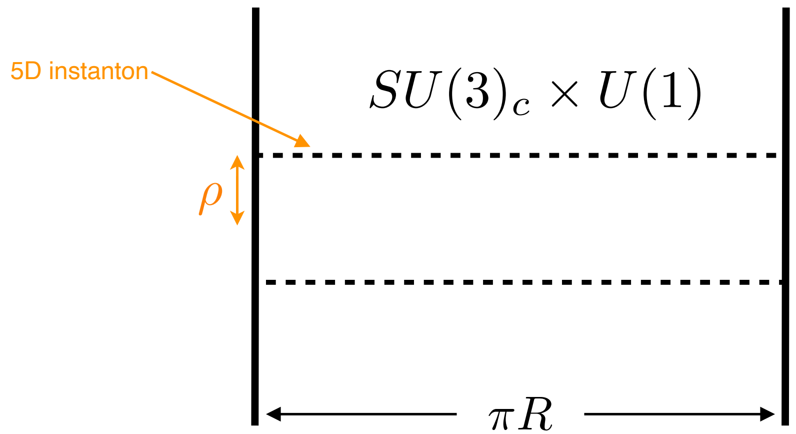
new contribution

Use 5th dimension to make QCD axion heavy!

QCD in 5D

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

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



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

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

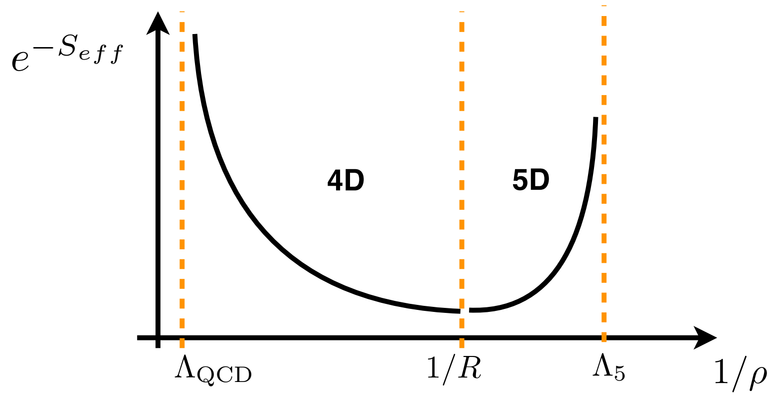
5D instanton: $A_\mu^a(x,y) = A_\mu^{(I)a}(x) = \frac{2\eta_{a\mu\nu}(x-x_0)_\nu}{(x-x_0)^2+\rho^2}, \quad A_5^a(x,y) = 0$

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

Finite action

5D small instantons

Fluctuations + Kaluza-Klein contributions



small instantons!

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

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

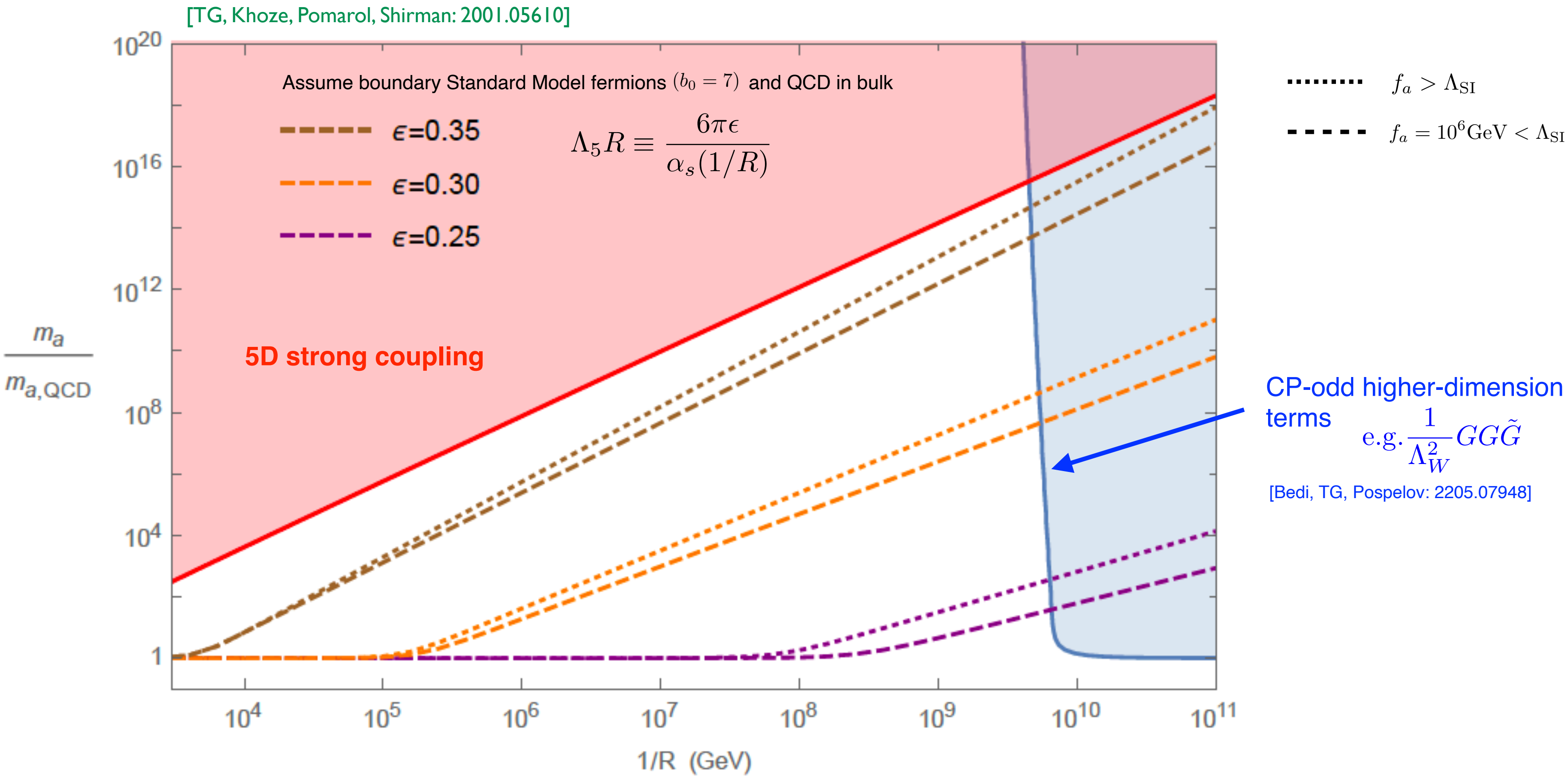
power law term!

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

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

power law contribution can overcome suppression

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



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

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: $\mathcal{L} \supset \sum_{ijkl} \frac{\lambda_{ijkl}}{\Lambda_F^2} \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$]

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

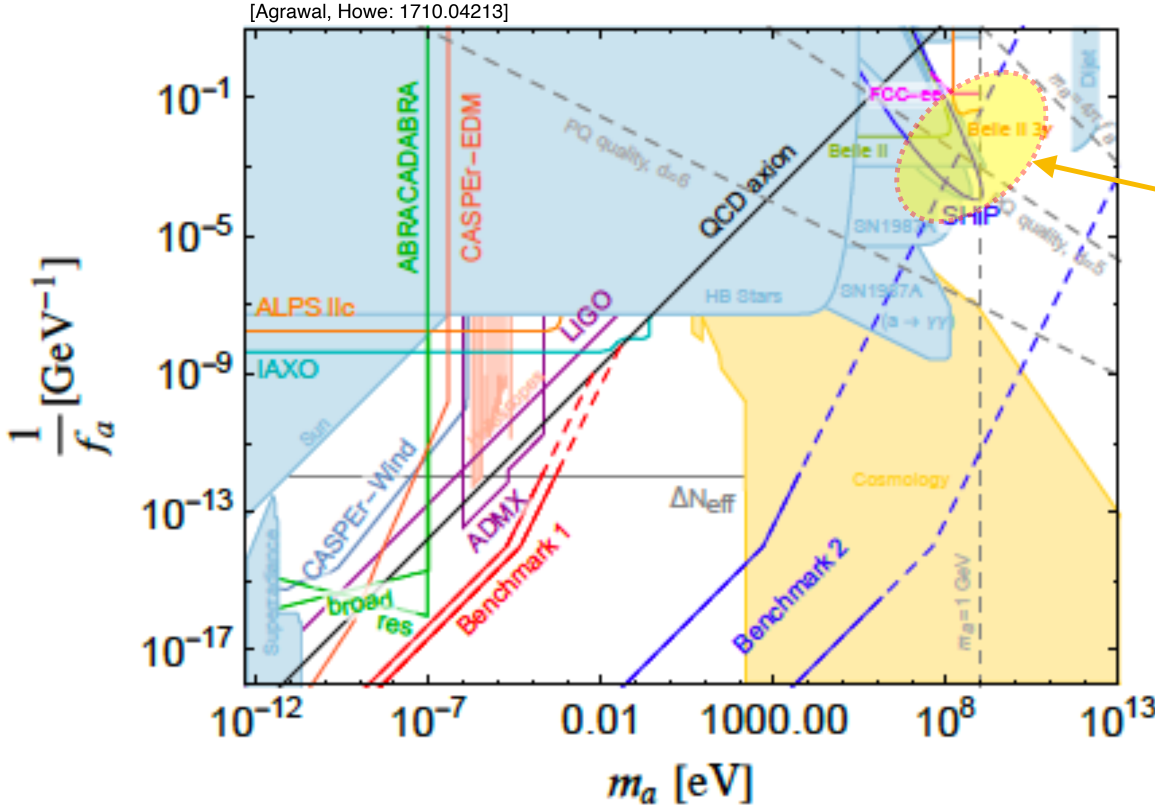
where $$\chi_W(0) = -i \lim_{k \to 0} \int d^4x \, e^{ikx} \left\langle 0 \left| T \left\{ \frac{1}{32\pi^2} G\widetilde{G}(x), \frac{1}{\Lambda_W^2} G G \widetilde{G}(0) \right\} \right| 0 \right\rangle$$

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

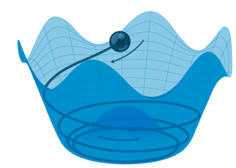
Neutron EDM: $|\theta_{\rm ind}| \lesssim 10^{-10}$ ⇨ $\frac{\Lambda_{\rm SI}}{\Lambda_W} \lesssim 10^{-6}$

Heavy Axion Limits

[Agrawal, Howe: 1710.04213]



Favoured by axiogenesis!
[Co, TG, Harigaya, 2206.00678]



Heavy QCD axion $(1\ \mathrm{MeV} - 10\ \mathrm{GeV})$
solves strong CP + baryon asymmetry!

Other possibilities:

- ***Strong QCD*** [Holdom, Peskin 1982] [Flynn, Randall 1987]

- ***Enlarge QCD color***

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

[Dimopoulos, Susskind '79; Dimopoulos '79]

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

[TG, Nagata, Shifman: 1604.01127]
[Gaillard, Gavela, Houtz, Quilez,del Rey: 1805.06465]
[Valenti, Vecchi, Xu: 2206.04077]

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

[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!

Summary

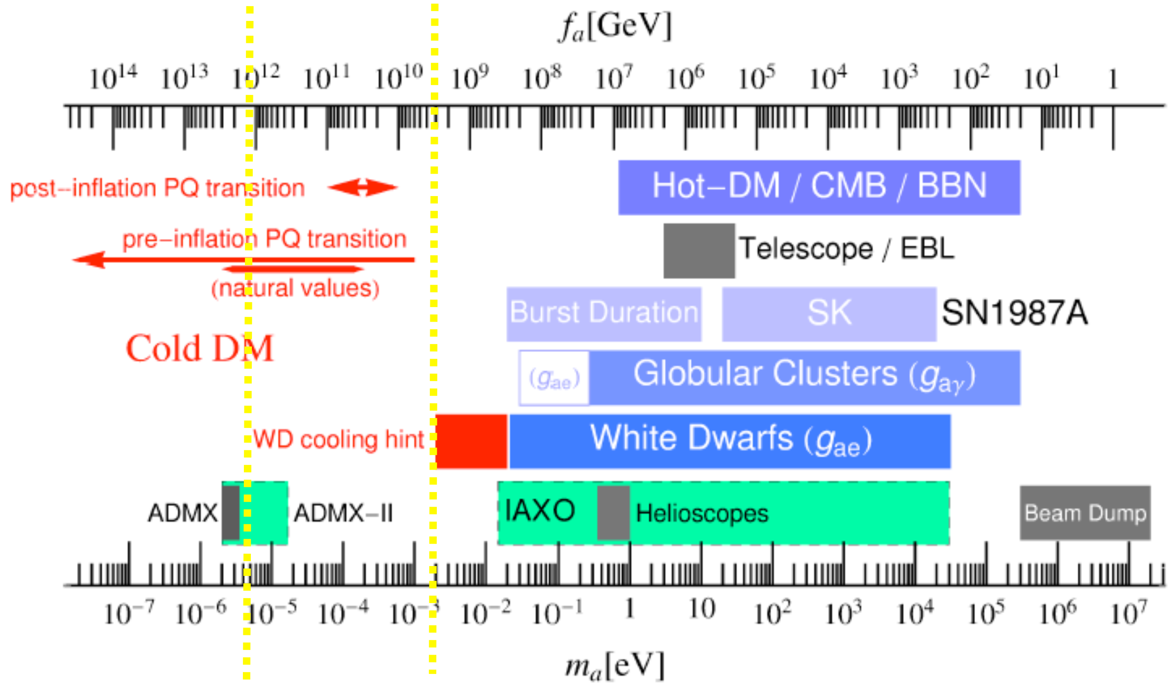
- Axion quality problem can be solved in 5D warped dimension
  - — *dual to 4D dynamical axion with accidental PQ symmetry*

- "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

QCD axion limits

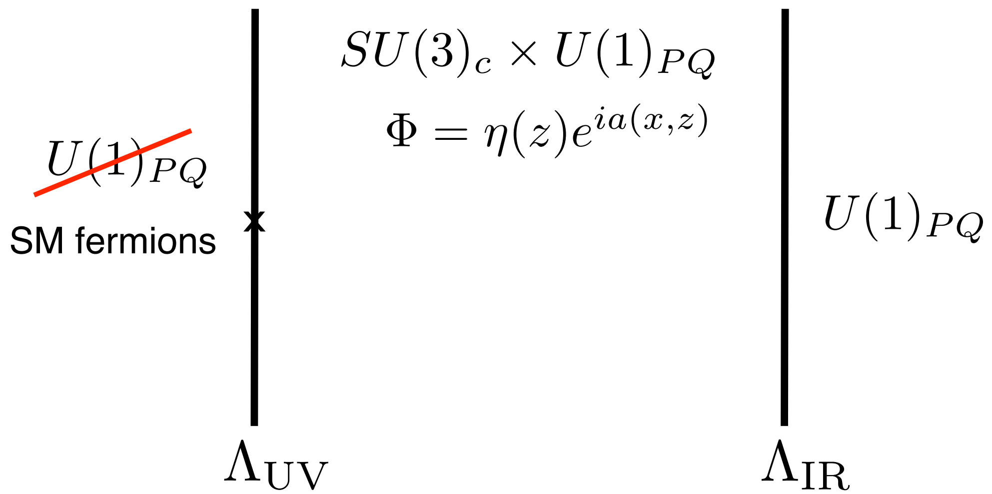


$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}$$

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

$m_a^2 f_a^2 \sim \frac{1}{8}\Lambda_{\rm QCD}^4$ ⇒ $10^{-5}\text{ eV} \lesssim m_a \lesssim 10^{-3}\text{ eV}$

Axion-Gluon Coupling



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

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

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

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

Obtain: $$S_{eff} = \int d^4x \left(\frac{1}{2}a^{(0)}\left(\Box - m_a^2\right)a^{(0)} + \frac{g_s^2}{32\pi^2 F_a}a^{(0)}G\tilde{G}\right)$$

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

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

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

Numerical results

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

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

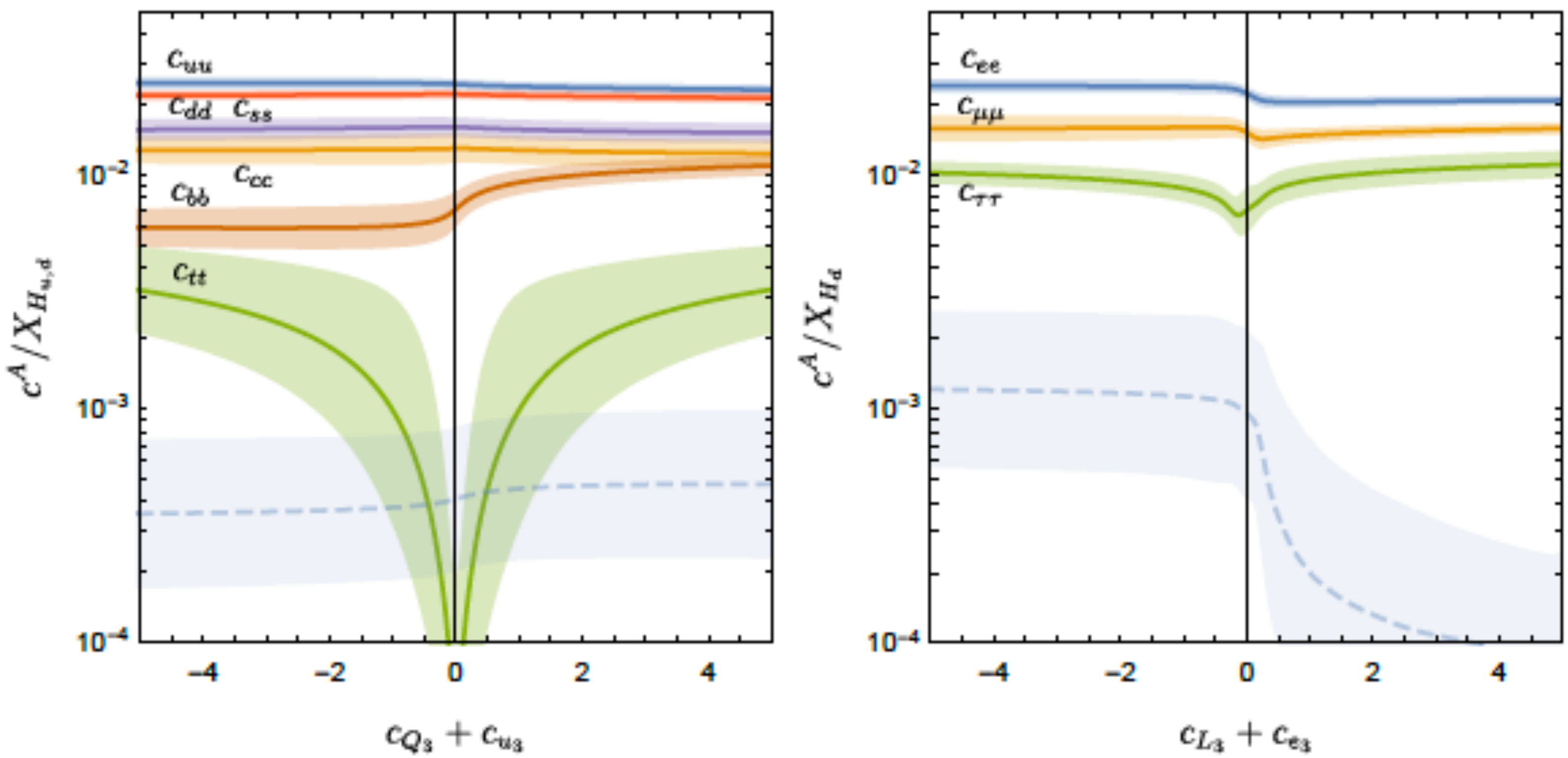
$\Delta = 10 \quad \sigma_0 = 3$

$F_a \simeq 10^9$ GeV.

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

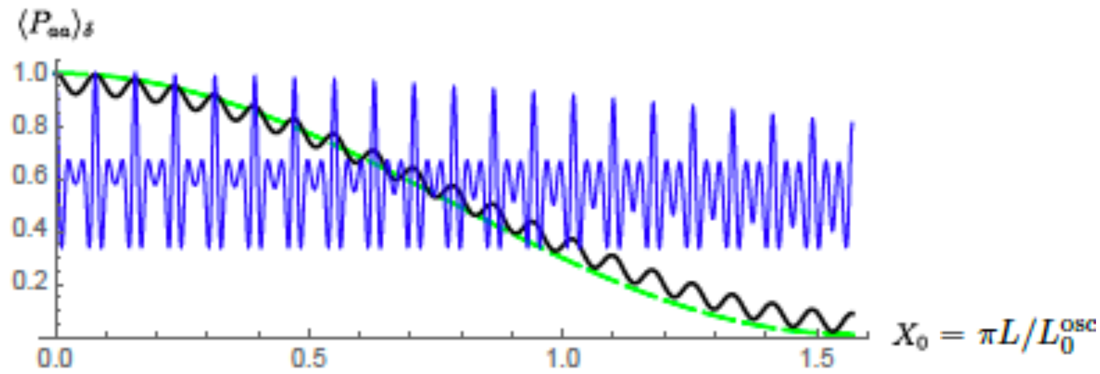
Flavor-preserving couplings:

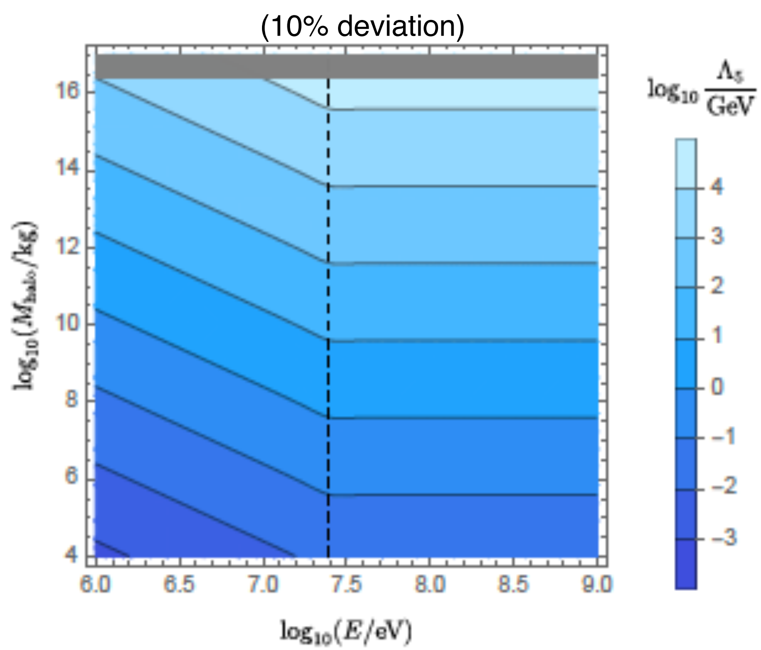
[Bonnefoy, Cox, Dudas, TG, Nguyen 2012.09728]



Results

Big halo $(\ell \sim R_\oplus)$





$m = 10^{-10}$eV

$\Delta m_0^2 = 2.5 \times 10^{-3}$eV^2

$\eta = 1$ (dashed line)

Higher dimension terms:

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

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

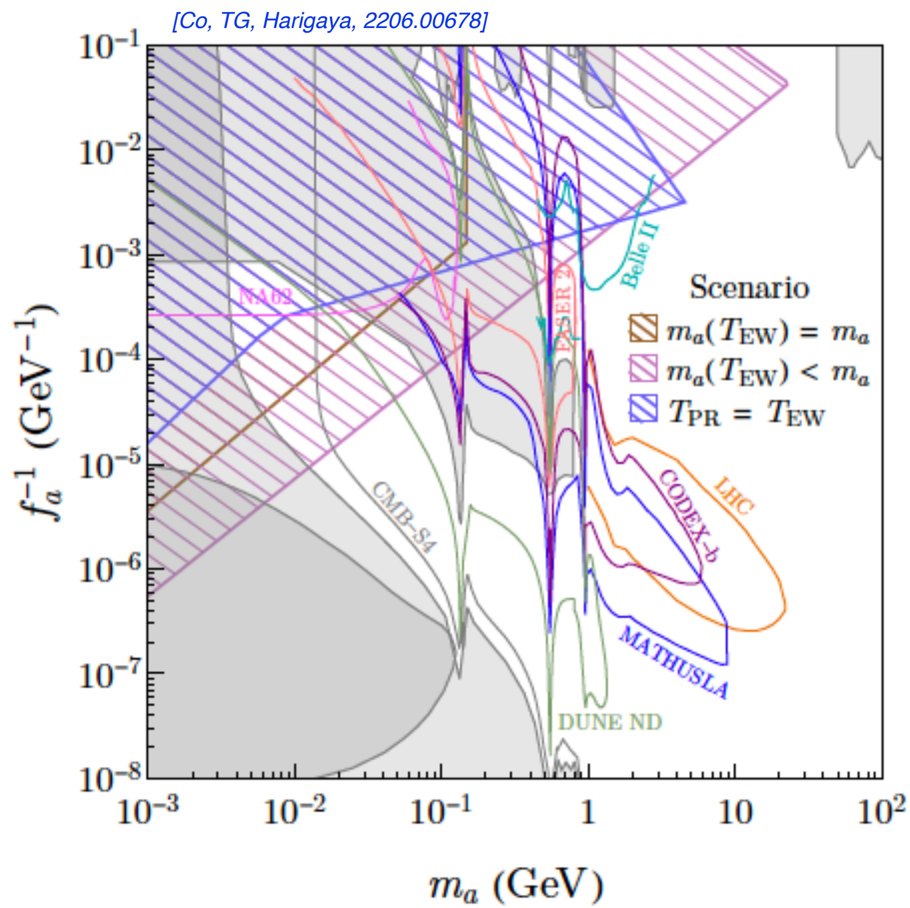
Higher dimension contribution

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

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



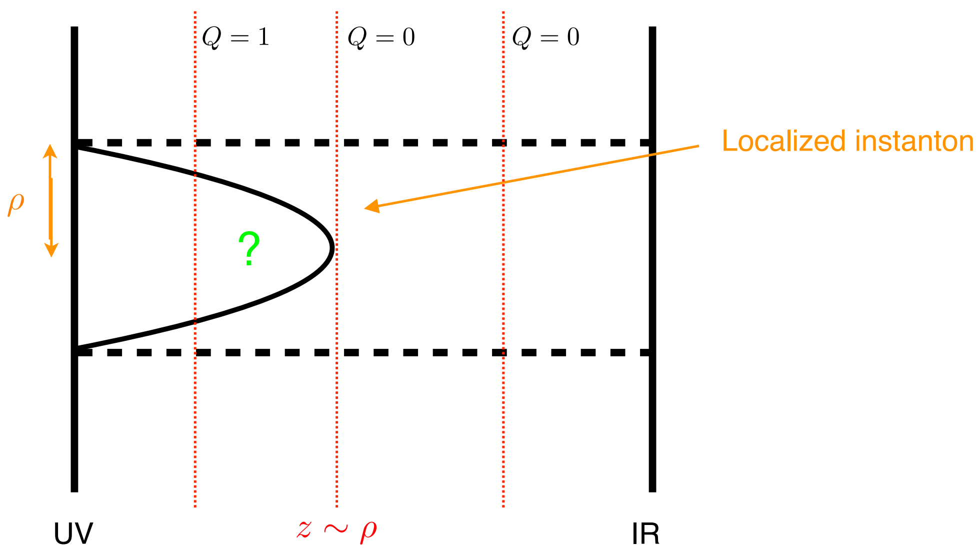
Heavy QCD axion solves strong CP + baryon asymmetry!

Localized Instanton?

[TG, Pomarol: 2110.01762]

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

Topological charge: $Q = \frac{1}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$



Axion mass: $m_a^2 f_a^2 \propto e^{-S}$

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

Larger axion mass enhancement compared to flat space?

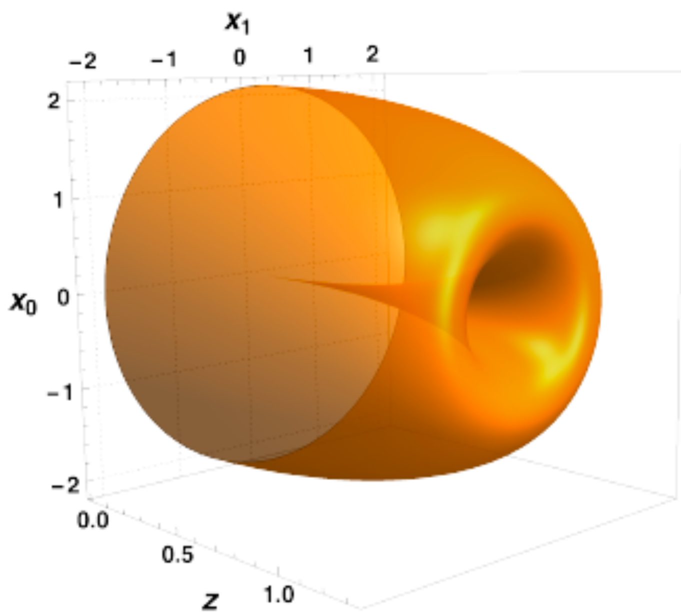
However, topological charge conservation → NO localized instanton!

→ CFT dual *necessarily* contains colored fermions!

Instead, obtain instanton-anti-instanton solution:

$$A^a_\mu(x,z) = 2\eta^a_{\mu\nu}\frac{x_\nu}{x^2}f(x,z)\ , \quad A^a_5(x,z)=0$$

where $f(x,z) = \dfrac{(x^2+z^2)^2}{x^2\rho^2+(x^2+z^2)^2}$



$$\Rightarrow \quad S = \frac{16\pi^2}{g_4^2(1/\rho)} \qquad Q = 0\ !$$

Also, obtain multi-instanton and new meron solutions [TG, Pomarol: 2110.01762]

e.g. 5D meron: $Q=\dfrac{1}{2}$ $\quad f(x,z)=\dfrac{1}{2}\dfrac{x^2}{x^2+\frac{3}{4}z^2}$