

5D perspectives on the axion/ALPs

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Extra dimension offers complete framework:

- Origin of PQ breaking potential and spontaneous breaking scale, f_a
 - explains hierarchies and can break symmetries with boundary conditions
 - *warped* dimension (slice of AdS) is dual to 4D strong dynamics!
- Axion quality problem
 - sequesters (non-QCD) explicit violation of PQ symmetry
- Standard Model flavour
 - explains fermion mass hierarchy and predicts axion-fermion couplings
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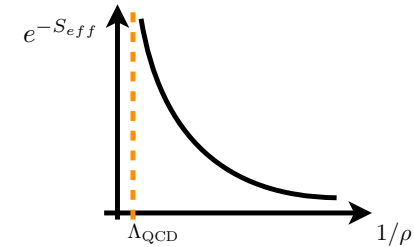
Anything else?

Axion mass

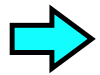
QCD axion: $m_a^2 = \frac{\mathcal{T}}{f_a^2}$ $\mathcal{T} \equiv -i \int d^4x \langle 0 | T \left[\frac{1}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}(x), \frac{1}{32\pi^2} G_{\rho\sigma}^b \tilde{G}^{b\rho\sigma}(0) \right] | 0 \rangle$ “topological susceptibility”

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

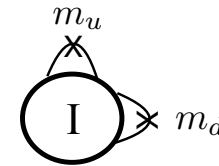


$$\mathcal{T} \propto \Lambda_{QCD}^4$$

“Large instantons” $\rho \sim 1/\Lambda_{QCD}$

Fermion zero modes:

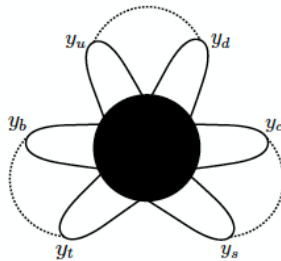
$$(\rho m_f)^{N_f} \longrightarrow \text{suppression} \frac{\prod_f m_f}{\Lambda_{QCD}^{N_f}}$$



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

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



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



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

new contribution

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

Use 5th dimension to make QCD axion heavy!

Other possibilities:

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]

Strong QCD

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

Mirror QCD

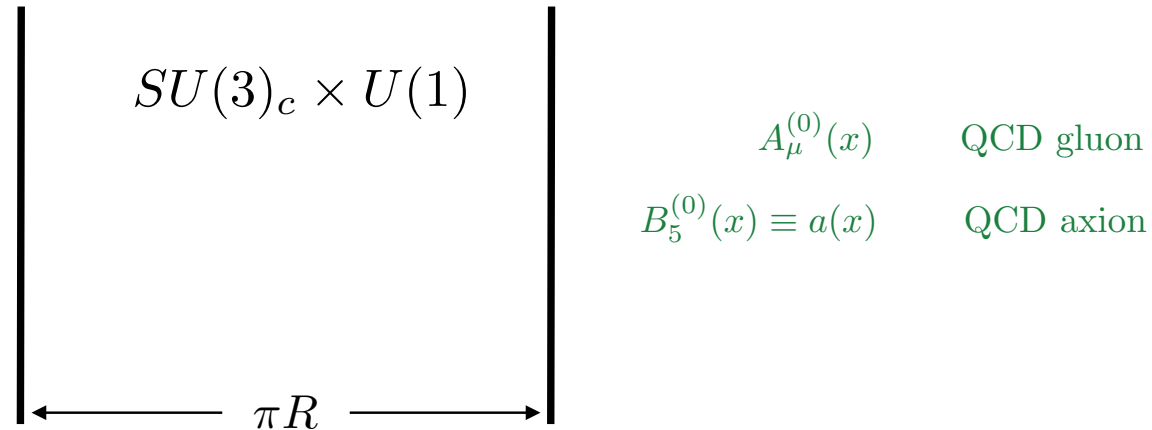
[Rubakov '97] [Berezhiani, Gianfagna, Gianotti '00]
[Dimopoulos, Hook, Huang, Marques-Tavares: 1606.03097]
[Hook, Kumar, Liu, Sundrum: 1911.12364]

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

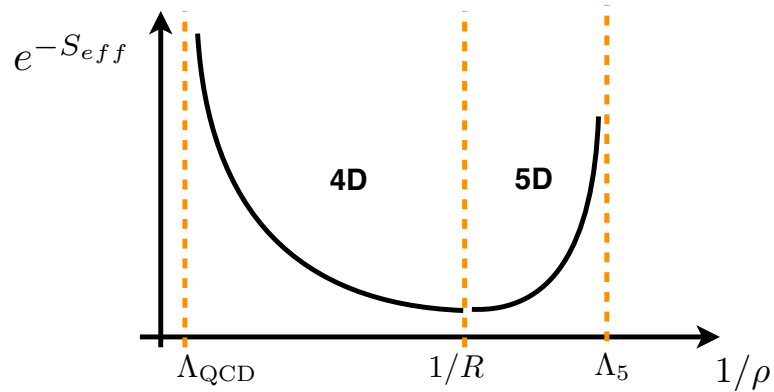


$$S_5^{(I)} = \frac{8\pi^3 R}{g_5^2} = \frac{2\pi}{\alpha_s}$$

Finite action

5D small instantons

Fluctuations + Kaluza-Klein contributions



small instantons!

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



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

power law term!

$$\xi(R/\rho) \sim 1/3 \quad R/\rho \gtrsim 20 \quad \Rightarrow \quad K \simeq C[3] \left(\frac{2\pi}{\alpha_s(1/R)} \right)^6 (\Lambda_5 R)^{3-b_0} e^{-\frac{2\pi}{\alpha_s(1/R)} + \Lambda_5 R}$$

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

[TG, Khoze, Pomarol, Shirman: 2001.05610]

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

Yukawa coupling suppression from Higgs loops 5D enhancement

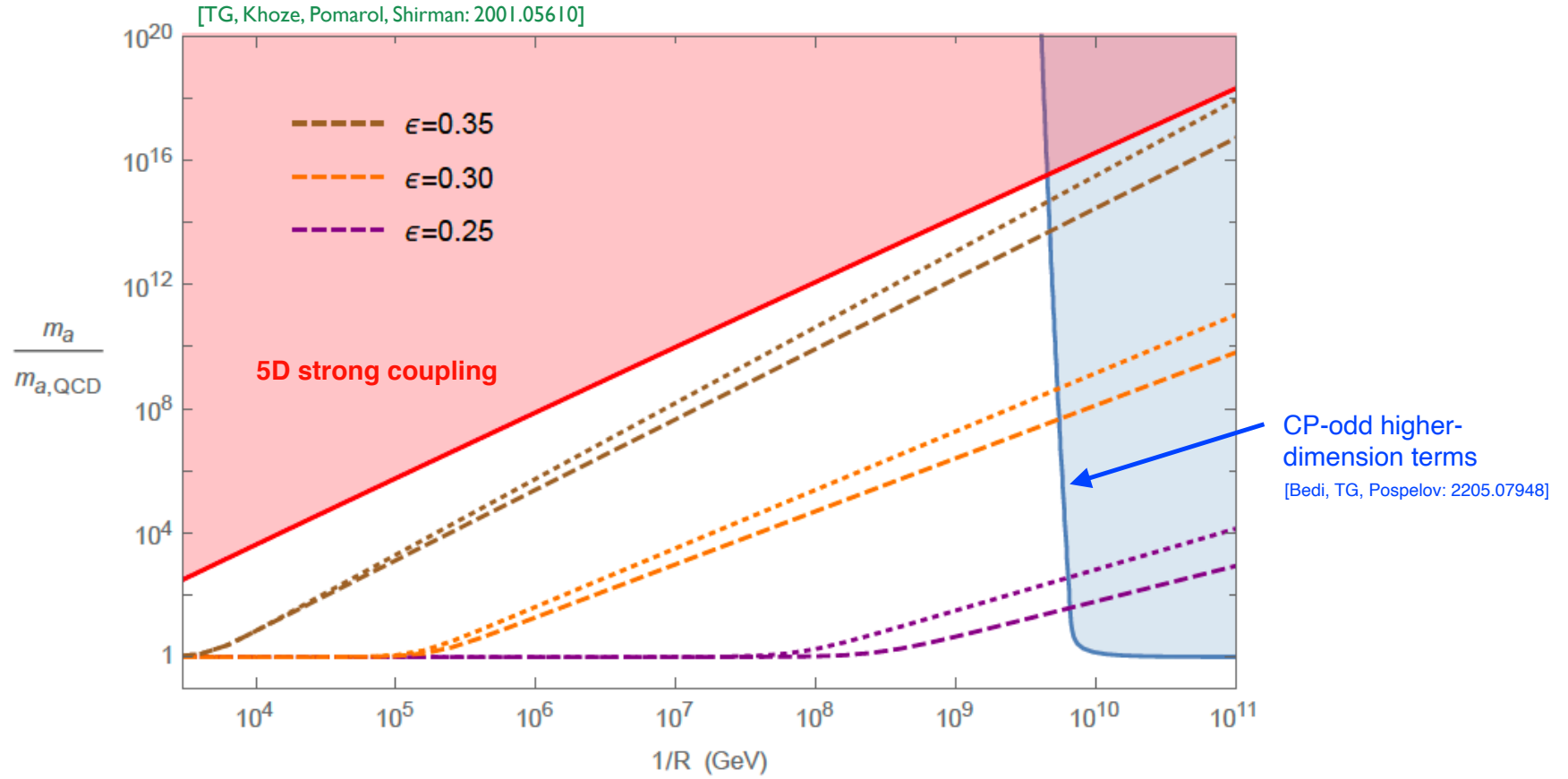


$$\frac{m_a}{m_{a,QCD}} \simeq \sqrt{2\kappa_f C[3]} \left(\frac{2\pi}{\alpha_s(1/R)} \right)^3 \frac{(m_u + m_d)}{\sqrt{m_u m_d}} \frac{1}{m_\pi f_\pi R^2} \frac{e^{-\frac{1}{2} \left(\frac{2\pi}{\alpha_s(1/R)} - \Lambda_5 R \right)}}{(\Lambda_5 R)^{\frac{1}{2}(b_0-3)}}$$

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

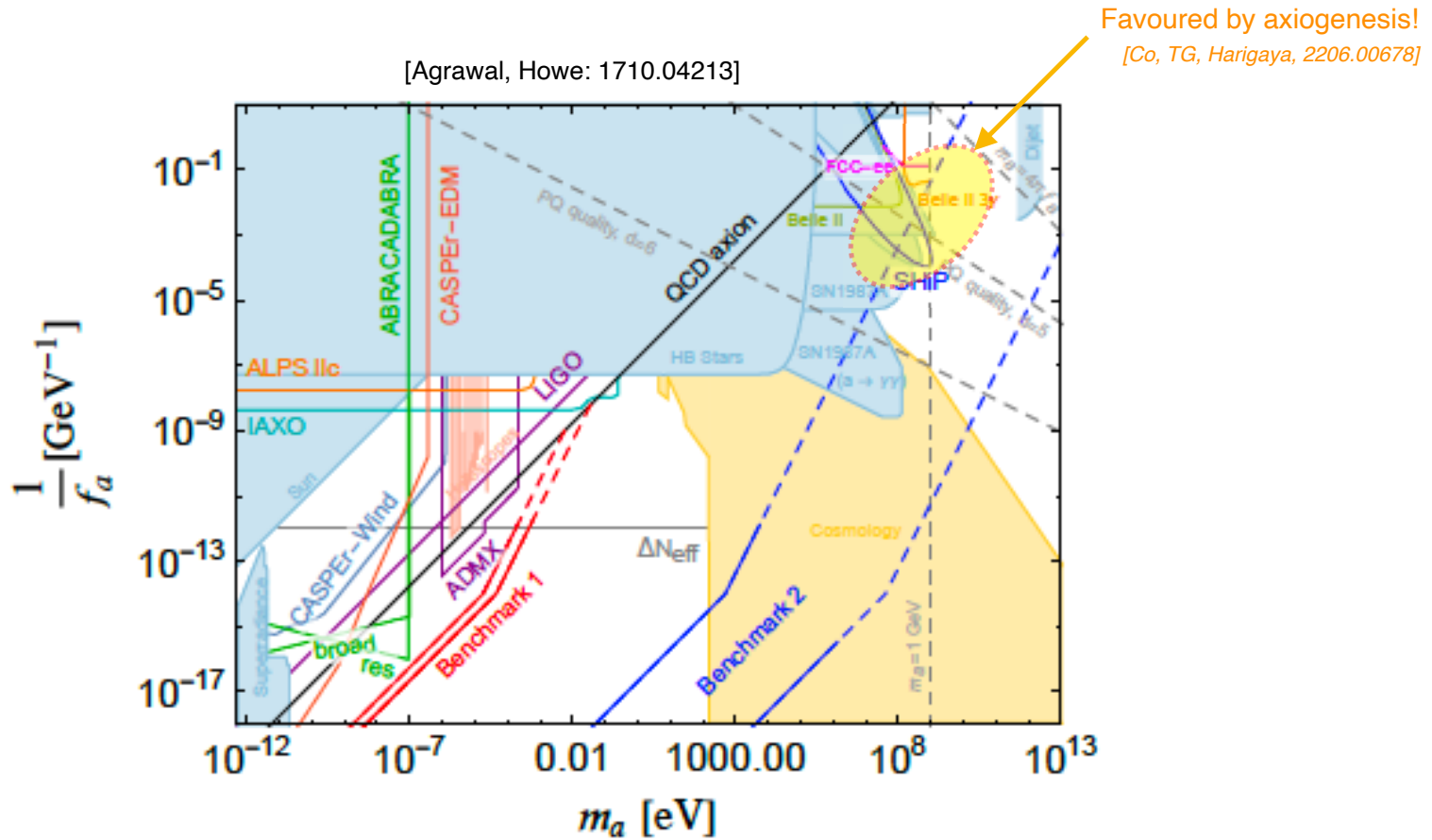
Positive exponent: $\frac{2\pi}{\alpha_s(1/R)} - \Lambda_5 R < 0 \quad \Rightarrow \quad \varepsilon \gtrsim 0.14$

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



Discussion Questions

Axion Quality

- Construct 4D dual models with $\Delta \geq 10$

Axion Flavour

- Generalize to z-dependent bulk Higgs VEVs
 - could enhance specific axion-fermion couplings
- Higgs and axion from same composite dynamics?

ALPs

- Dark matter ALPs with axion-fermion couplings?
- Dark energy ALP?
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Axion Mass

- 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?

- An even lighter QCD axion in extra dimensions?

[Hook: 1802.10093] [Di Luzio, Gavela, Quilez, Ringwald: 2102.00012]

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