

# Holographic Chiral Anomalies and Axions

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# Outline

- ① Strong CP Problem  
Axion Solution  
Axion Quality Problem
- ② Holographic Composite Axion  
Anomaly Flow
- ③ Phenomenology



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# Strong CP Problem

Or why  $\bar{\theta}$  is so small?

$$\mathcal{L}_{QCD} \supset \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta - \arg \det M_q$$

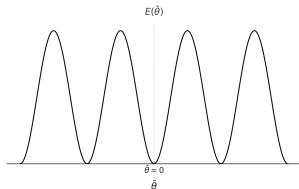
- CKM phase  $\phi$  must be of  $O(1)$  to explain observed CP violation in K and B-meson systems.
- But we know  $\bar{\theta} \lesssim 10^{-13}$  from neutron eDM non-observations.
- There is no symmetry or mechanism in SM responsible to take  $\bar{\theta}$  small.

# Axion Solution

- SM is enhanced by a global  $U(1)_{PQ}$  symmetry, broken spontaneously at a scale  $f_{PQ}$  - produces a Goldstone boson
- A new pseudoscalar degree of freedom, **the axion  $a$**
- PQ symmetry is broken by **anomalies**, which results in non-derivative interaction.

$$L = \left( \frac{a}{f_{PQ}} + \bar{\theta} \right) \frac{1}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + V(a)$$

- QCD vacuum energy minimize as axion rolls to min of the potential.

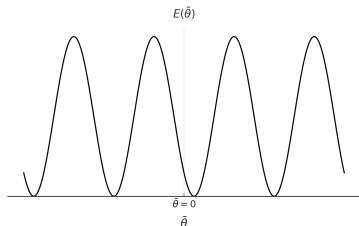


Strong CP problem solved!

# Axion Quality Problem

However...

- Lore: Quantum Gravity breaks global symmetries, including  $U(1)_{PQ}$ , represented by Planck scale suppressed operators.
- Such a explicit breaking effects contribute to axion potential and shift the min.



Back to strong CP problem!

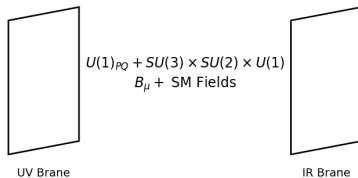
# Holographic Composite Axion

# Holographic Composite Axion

Our solution:

Holographic composite axion.

L. Randall, Phys. Lett. B **284** (1992), 77-80



$U(1)_{PQ}$ : abelian gauge symmetry in the bulk broken by boundary conditions on branes: dual to spontaneously broken **global**  $U(1)_{PQ}$

D. Bunk and J. Hubisz, Phys. Rev. D **81** (2010), 125009 [arXiv:1002.3160 [hep-ph]].

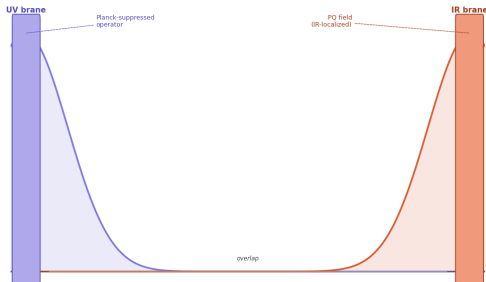
# Holographic Composite Axion

- $B_\mu|_{z=R, R'=0} = 0$ :  $B_5$  zero mode (Goldstone boson!)
- The effective scale of symmetry breaking of this Goldstone boson:

$$f_{\text{PQ}} = \frac{1}{\sqrt{2}R'} \frac{\sqrt{R}}{g_{5D}}$$

- Two ways to have a phenomenologically viable  $f_{\text{PQ}}$ :  
Small  $R'$ , or small  $g_{5D}$
- Latter choice:  $f_{\text{PQ}}$  suppressed by large  $N$  effects in dual CFT, actual breaking scale  $1/R'$  (and new resonances) can be  $\mathcal{O}$  TeV!

# Holographic Composite Axion as a Solution to Axion Quality Problem



- The  $B_5$  wave function is IR localized, and since 4D gravity is UV localized, PQ violating operators suppressed by powers of  $(R/R') \sim (TeV/M_{Pl})$
- Only dimension 5 operators require additional suppression - dimension 6 and higher sufficiently suppressed by wave function overlap.

# Holographic Composite Axion: Couplings to Fermions

- Goldstone nature revealed by field redefinition

$$\Psi(z, x) = \exp\left(iq \int_{z_0}^z dz' B_5(x, z')\right) \Psi'(z, x)$$

- After redefinition,  $\Psi'$  transforms globally under the PQ gauge symmetry,  $B_5$  interacts derivatively

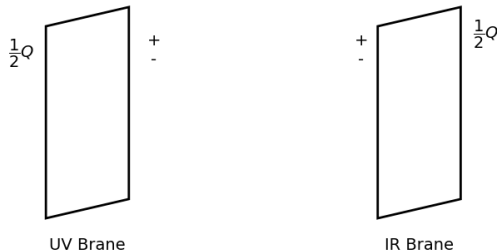
$$\bar{\Psi} i \not{D} \Psi \rightarrow \bar{\Psi}' i \not{D}_4 \Psi' - \bar{\Psi}' i \gamma^5 \partial_5 \Psi' - q \int_{z_0}^z dz' (\partial_\mu B_5(z')) \bar{\Psi}' \gamma^\mu \Psi'$$

- If fermions get mass on the IR brane (e.g. from IR localized Higgs), choose  $z_0 = R'$  for most convenient parametrization of action

$$M \bar{\Psi}_L \Psi_R + \text{h.c.} \rightarrow M \exp(i(q_R - q_L) \int_{R'}^{z_0} dz' B_5) \bar{\Psi}'_L \Psi'_R + \text{h.c.}$$

# 5D Anomalies

## 5D Anomalies



- Known that in 5D, fermionic contribution to anomalies are localized on the branes:

$$\begin{aligned}
 A(x, z) &= \frac{1}{2} [\delta(z - R) + \delta(z - R')] \sum_f q^f \left( \frac{q_Y^f}{16\pi^2} F \cdot \bar{F} + \frac{\text{Tr } \tau_a^f \tau_a^f}{16\pi^2} W \cdot \bar{W} \right) + \frac{\text{Tr } t_a^f t_a^f}{16\pi^2} G \cdot \tilde{G} \\
 &\equiv \frac{1}{2} [\delta(z - R) + \delta(z - R')] Q(x, z)
 \end{aligned}$$

N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **516** (2001), 395-402 [arXiv:hep-th/0103135 [hep-th]].

## 5D Anomalies

- Field redefinition on previous slide results in non-derivative couplings through the anomaly:

$$S_{anomaly} = -\frac{1}{2} \int d^4x \left[ \int_{z_0}^R dz' B_5 Q(R, x) - \int_{R'}^{z_0} dz' B_5 Q(R', x) \right]$$

- Puzzle:** Anomaly on IR brane did not contribute to  $B_5$  couplings to gauge fields for  $z_0 = R'$ ! Coupling is smaller by factor of 1/2 than in comparable PQ axion models.
- Having anomaly split across IR and UV problematic for other reasons.

# Anomaly Flow

- We can use Chern Simons Term and choose its coefficient such that:

UV Brane IR Brane

$$S_{CS} = c \int d^5x \sqrt{g} \epsilon^{ABCDE} B_A F_{BC} F_{DE}$$

$$\in c \int d^4x g_{5D} \frac{1}{\sqrt{2}} \sqrt{\frac{R'^2 - R^2}{R}} B_5^{(0)}(x) F\tilde{F}$$

$$c = \frac{\pm 1}{32\pi^2}$$

- Now the  $aF\tilde{F}$  coupling coefficient matches the one expected for a particular choice of PQ charge assignments (e.g. KSVZ or DFSZ)

# Phenomenology

Gravitational interactions in the 5D bulk, unsuppressed by  $f_{PQ}$ : the couplings of the excitations of RS gravity to the physical  $B_5$  Goldstone bosons.

$r B^{(1)\mu} \partial_\mu B_5$	$1.09 \frac{M_1}{\kappa \Lambda_r}$	$\hat{h}_{(1)}^{\mu\nu} B_\mu^{(1)} \partial_\nu B_5$	$-0.134 \frac{M_1}{\kappa \Lambda_1}$	$\hat{h}_{(2)}^{\mu\nu} B_\mu^{(1)} \partial_\nu B_5$	$.099 \frac{M_1}{\kappa} \Lambda_2$
$r B_\mu^{(1)} B^{(1)\mu}$	$\frac{4}{3} \frac{M_1^2}{2\kappa \Lambda_r}$	$\hat{h}_{(1)}^{\mu\nu} B_\mu^{(1)} B_\nu^{(1)}$	$-.137 \frac{M_1^2}{2\kappa \Lambda_1}$	$\hat{h}_{(2)}^{\mu\nu} B_\mu^{(1)} B_\nu^{(1)}$	$.050 \frac{M_1^2}{2\kappa \Lambda_2}$
$r B_{\mu\rho}^{(1)} B^{(1)\mu\rho}$	$\frac{1}{3} \frac{1}{2\kappa \Lambda_r}$	$\hat{h}_{(1)}^{\mu\nu} B_{\mu\rho}^{(1)} B_\nu^{(1)\rho}$	$.137 \frac{1}{2\kappa \Lambda_1}$	$\hat{h}_{(2)}^{\mu\nu} B_{\mu\rho}^{(1)} B_\nu^{(1)\rho}$	$.053 \frac{1}{2\kappa \Lambda_2}$
$r (\partial_\mu B_5)^2$	$2 \frac{1}{2\kappa \Lambda_r}$	$\hat{h}_{(1)}^{\mu\nu} \partial_\mu B_5 \partial_\nu B_5$	$-.219 \frac{1}{2\kappa \Lambda_1}$	$\hat{h}_{(2)}^{\mu\nu} \partial_\mu B_5 \partial_\nu B_5$	$.049 \frac{1}{2\kappa \Lambda_2}$

Lagrangian coefficients for interactions between RS gravitational excitations and the modes associated with the bulk gauge symmetry that produces light Goldstone modes.

# Phenomenology

There are two qualitatively different possibilities for axion cosmology depending on when  $PQ$  symmetry breaks:

- Breaking during inflation: The axion fluctuations can lead to **isocurvature** modes, which are constrained:  $\frac{H_I}{f_I} < 10^{-8} < 2.8 \times 10^{-5}$

Graham, Peter W. and Racco, Davide, JHEP 12 (2025) 028 [arXiv:2506.03348 [hep-ph]]

- Breaking after inflation: The breaking of global symmetries may give rise to topological defects, such as axion string and domain walls.
  - The topology of the extra dimensional model may modify these (work in progress)

# Conclusion

- The holographic composite axion offers a partial solution to the axion quality problem.
- Large  $N$  effects (a small 5D gauge coupling) can lead to a suppression of axion interactions leading to phenomenologically viable models with large PQ breaking scale.
- Understanding the anomaly localization structure is crucial to obtaining the right coupling of the axion to photons.
- New interactions of the axion with KK modes/composite resonances suppressed only by the TeV scale and may be accessible at future experiments.
  - The Chern-Simons term plays a crucial role in holographic composite axion model.

Thank You!

