A QCD axion from Randall-Sundrum type models

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(JHEP 0701:061,2007 [hep-ph/0611278])

The QCD Axion in RS-type models: Outline

- The Strong CP problem and axions
- RS-type models and multi-throats
- $f_{PQ} \sim 10^{12}$ GeV from RS-type models

The Strong CP problem

- QCD admits instanton solutions which lead to a non-trivial QCD vacuum.
- Effective contribution of the non-trivial QCD vacuum:

$$\mathcal{L}_\theta = i\overline{\theta}\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{a\mu\nu},$$

  where $\overline{\theta} = \theta - \arg\det M_q$ is an a priori free parameter.
- QCD *predicts* CP violation!
- Empirically (neutron EDM) $\overline{\theta} \lesssim 10^{-9}$
  $\rightarrow$ fine-tuning between the θ vacuum and the phase of the quark mass matrix.

The axion

- Peccei, Quinn, Weinberg, Wilczek:
  - Promote $\overline{\theta}$ to a field a.
  - Realize a as Goldstone boson of a global $U(1)_{PQ}$, spontaneously broken at f_{PQ}.
    (To avoid radiative corrections to the potential.)
  - Implement a $U(1)_{PQ} \times SU(3)_c^2$ (QCD) anomaly.
  - Non-derivative coupling:

$$\mathcal{L}_a = \frac{a}{32\pi^2 f_{PQ}} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}.$$

  - QCD anomaly induces $V(a) \propto (1 - \cos(a/f_{PQ}))$
  - $m_a^2 \sim \Lambda_{QCD}^4 / f_{PQ}^2$.
  - Thus $\overline{\theta} = 0$ is obtained dynamically at the expense of introducing a new scale: f_{PQ}.

Experimental constraints on the axion

- A (model dependent) $U(1)_{PQ} - U(1)^2_{em}$ anomaly induces

$$\mathcal{L}_a = \xi e^2 \frac{a}{32\pi^2 f_{PQ}} F^{(em)}_{\mu\nu} \tilde{F}^{(em)\mu\nu}.$$

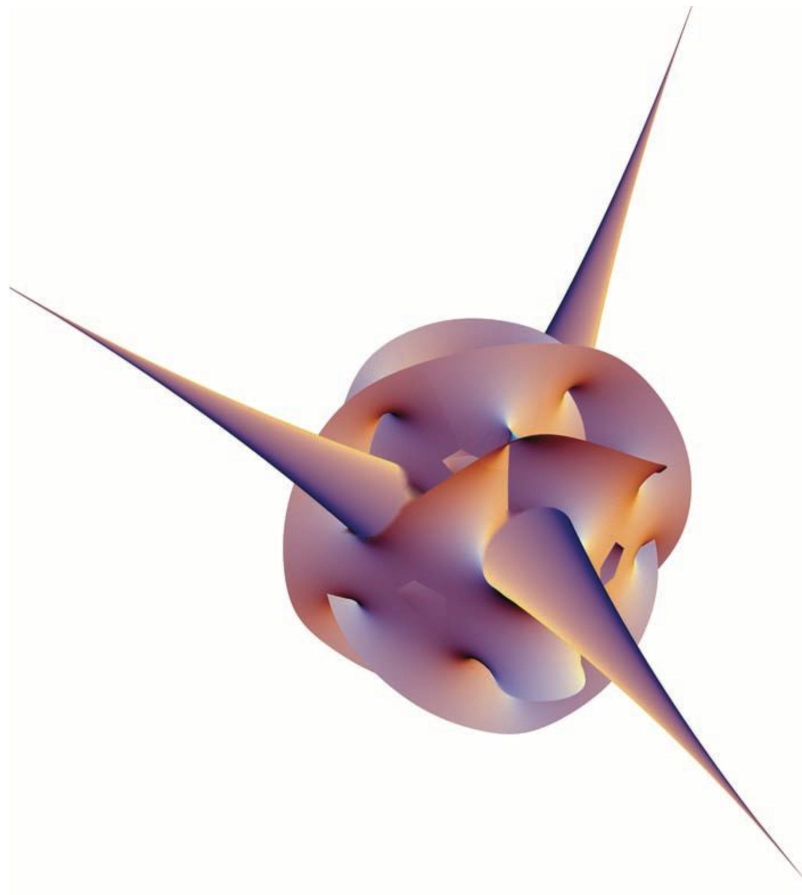
  - Astrophysics (cooling of HB stars/super-novae).
  - Searches for axions from the sun. (CAST, ...)
  - Axion to photon conversion in magnetic fields. (PVLAS*, BFRT, ALPS,...)
- Upper bound: avoid overclosure from coherent axion energy density.
- $10^9\,\mathrm{GeV} \lesssim f_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$ $(10^{-5}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-2}\,\mathrm{eV})$ / *
- **To solve the strong CP problem via (standard) axions, a new scale $\mathbf{10^9\,GeV \lesssim f_{PQ} \lesssim 10^{12}\,GeV}$ has to be introduced!**

RS-type models and multi-throats

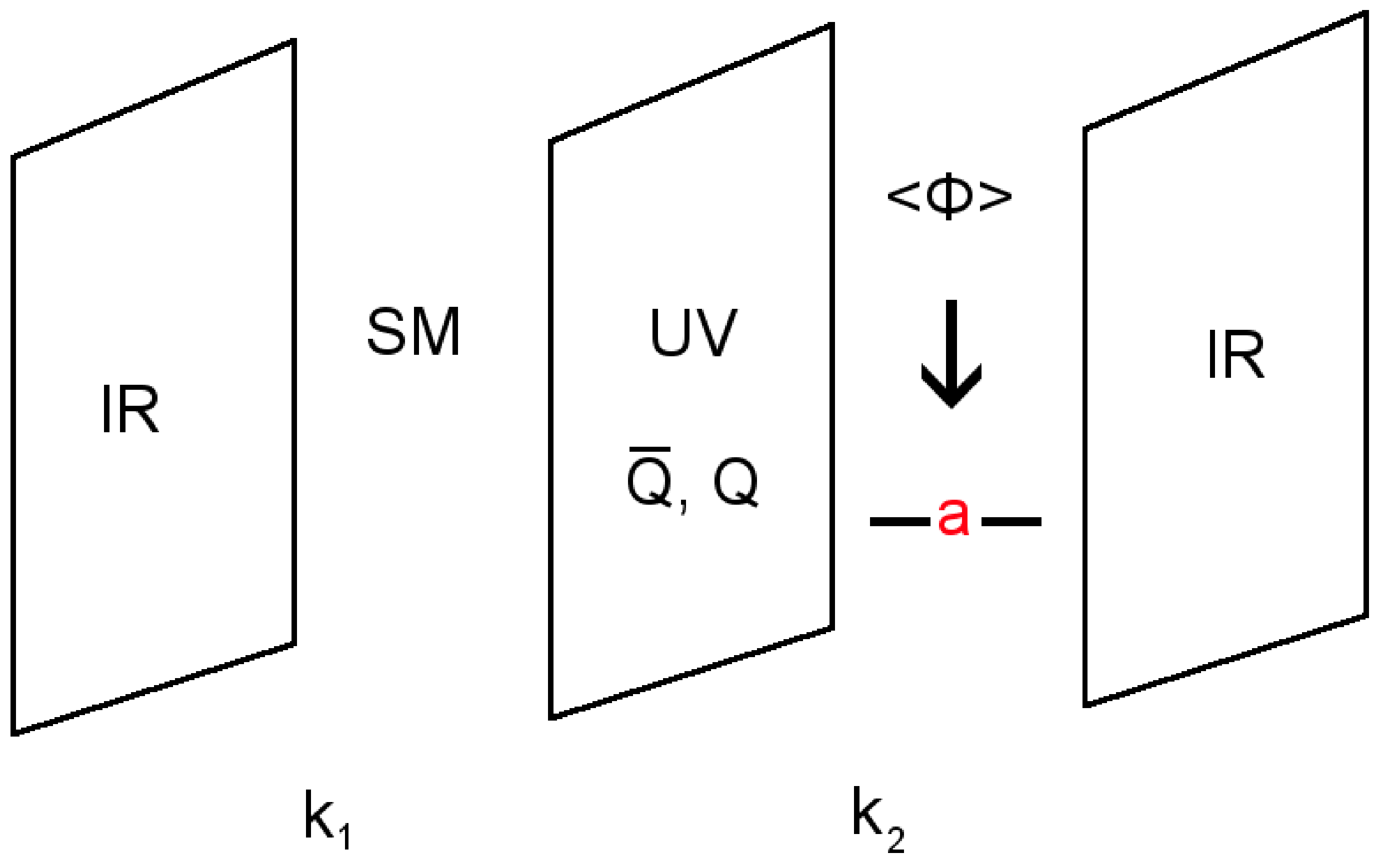
- Randall and Sundrum:
  Large hierarchies in energy scales can be realized by compactification on AdS_5:
  - $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \equiv (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$
- The M_{EW}/M_{Pl} hierarchy is explained through an exponential red-shifting of scales due to the localization of the Higgs on the IR brane.
- Hierarchies in couplings can be re-interpreted geometrically (in terms of localization of bulk fields).
- 4D dual interpretation via the AdS/CFT correspondence.
- Warped models are possible (parts of) low-energy realizations of string compactifications.

RS-type models and multi-throats

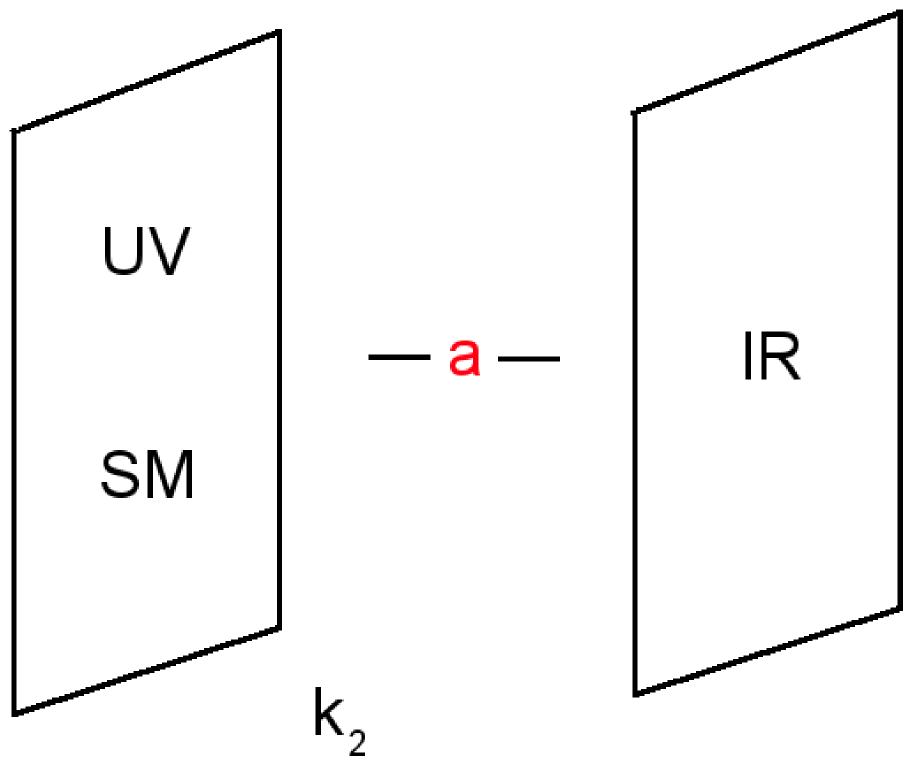
from: Cacciapaglia, Csaki, Grojean, Terning, Phys.Rev.D74:045019,2006



The QCD Axion from an RS-type model



The QCD Axion in RS-type models



The QCD Axion in RS-type models

We consider two basic possibilities to obtain a pseudo-scalar from the 5D theory:

- Realize the axion as a complex scalar field in the axion throat.
  - $U(1)_{PQ} \times SU(3)_c^2$ anomaly via heavy quarks.
- Realize the axion as the 5-component of a U(1) gauge field in the axion throat.
  - $U(1)_{PQ} \times SU(3)_c^2$ via a Chern-Simons term.

The QCD Axion from a 5D gauge field

- Consider a $U(1)$ bulk gauge field with b.c.'s

$$A_\mu\Big|_{\rm bdy} = 0, \qquad \partial_5 \left(\frac{A_5}{z}\right)\Bigg|_{\rm bdy} = 0$$

- $A_\mu^{(0)}$ are projected out. $A_5^{(0)}$ survives $\rightarrow$ massless scalar degree of freedom in terms of the 4D effective theory.
- Can show that the 5D $U(1)$ gauge symmetry manifests itself in a (global) shift symmetry on $A_5^{(0)}$.
- Solution for the $A_5^{(0)}$ profile: $A_5(x,z) = Nza(x)$
- Canonical normalization $\rightarrow N \approx \sqrt{2kg_5^2}/L_1$

The QCD Axion from a 5D gauge field

In order to couple A_5 to the QCD anomaly, we use the 5D Chern-Simons term

$$\epsilon^{LMNPQ} A_L F^a_{MN} F^a_{PQ}$$

For a UV localized interaction, the coupling term becomes

$$S_{int} = \int d^4x \frac{\alpha}{64\pi^2 M_5} A_5 \Big|_{\mathrm{UV}} \epsilon^{\mu\nu\lambda\sigma} F^a_{\mu\nu} F^a_{\lambda\sigma}.$$

Get f_{PQ} by canonical normalization of a_0:

$$f_{PQ} = \frac{M_5 k L_1}{\sqrt{2kg_5^2}} \sim M_5^2 L_1 \gg M_5 \sim M_{\mathrm{pl}}.$$ FATAL!

The QCD Axion from a 5D gauge field

Modification: allow for a CS term in the whole axion bulk (implying that QCD propagates in the axion throat!)

- *Cf.* K. Choi,[PRL**92**,101602] for this ansatz, but assuming all fields in the SM throat.

the QCD anomaly "sees" the IR localization of A_5^0:

$$f_{PQ} = \sqrt{\frac{2}{k g_5^2}} \frac{1}{L_1} \simeq \frac{M_{\rm pl}}{M_5 L_1}.$$

$f_{PQ} = 10^{12}\,{\rm GeV}$ realized by a "short" throat (warping $\sim 10^6$).

Summary and Conclusions

- We studied a RS two-throat setup with a Standard Model and an axion throat (with identical curvatures).
- A 4D effective axion can be obtained from
  - The phase of a complex bulk scalar.
  - The 5 component of a U(1) bulk gauge field with appropriate boundary conditions.
- In both cases, the coupling to the QCD anomaly can be achieved by introducing additional colored, PQ charged fermions.

Summary and Conclusions

Results:

- The simplest realizations fail: QCD has to propagate in both bulks.
- For a complex scalar with IR localized coupling to QCD, can achieve $f_{PQ} \sim 10^{12}$ for "mild" warping $kL_1 \sim 10^6$.
- For a U(1) gauge field with bulk localized coupling to QCD, $f_{PQ} \sim 10^{12}$ can be achieved for $kL_1 \sim 10^6$.
- The AdS/CFT dual of the axion from a U(1) gauge field leads to a composite axion model.

Dual interpretation of the axion from a 5D gauge field

following Contino, Nomura, Pomarol Nucl.Phys B **671**, 148 [hep-ph/0306259]

5D $U(1)$ gauge symmetry	$\leftrightarrow$	global $U(1)$ symmetry
IR Dirichlet b.c. on A_μ	$\leftrightarrow$	global $U(1)$ is spont. broken
$\rightarrow$ IR Neumann b.c. on A_5	$\leftrightarrow$	Goldstone boson (a)
A_5 is IR localized	$\leftrightarrow$	a is composite
UV Dirichlet b.c. on A_μ	$\leftrightarrow$	$U(1)$ is explicitly broken
$\rightarrow$ UV Neumann b.c. on A_5	$\leftrightarrow$	a acquires a (small) mass