A QCD axion from Randall-Sundrum type models

Thomas Flacke

TF , John March-Russell, David Maybury, Ben Gripaios

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

The QCD Axion in RS-type models: Outline

- The QCD vacuum and the Strong CP problem
- The Axion Solution in 4D
- RS-type models and multi-throats
- $f_{PQ} \sim 10^{12}$ GeV from RS-type models
- Summary and Conclusions

The QCD vacuum and the strong CP problem

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

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

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

The Axion Solution in 4D

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

Experimental constraints on the 4D axion

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

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

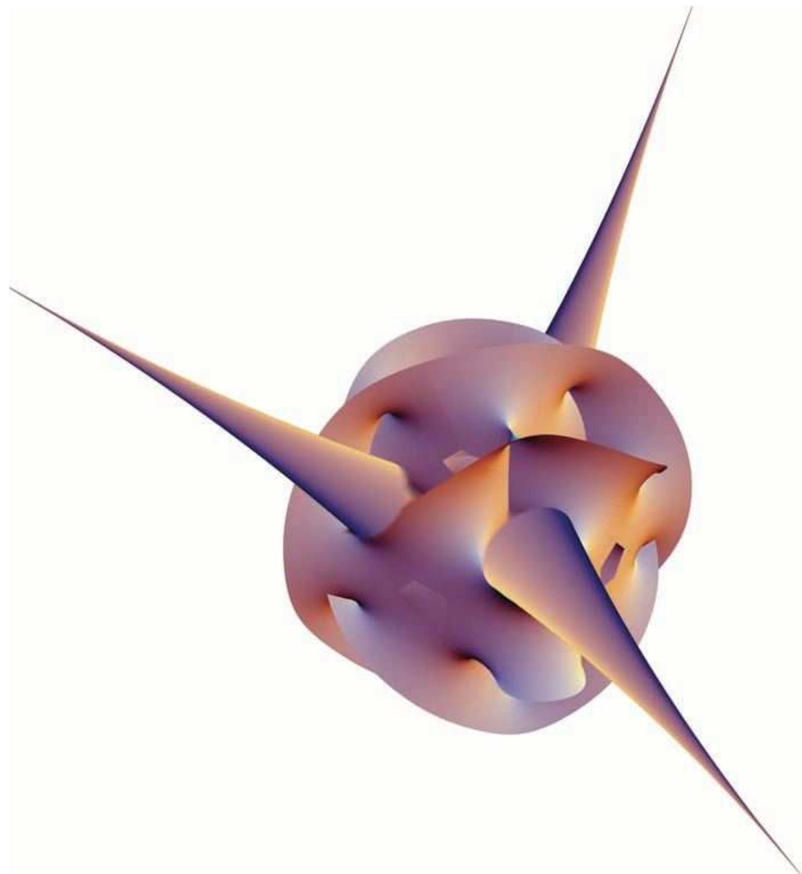
  - Astrophysics (cooling of HB stars/super-novae).
  - Searches for axions from the sun. (CAST, ...)
  - Axion to photon conversion in magnetic fields. (PVLAS*, BFRT, ALPS,...)
- Upper bound: avoid overclosure from coherent axion energy density.
- $10^9\,\mathrm{GeV} \lesssim f_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$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

RS-type models and multi-throats

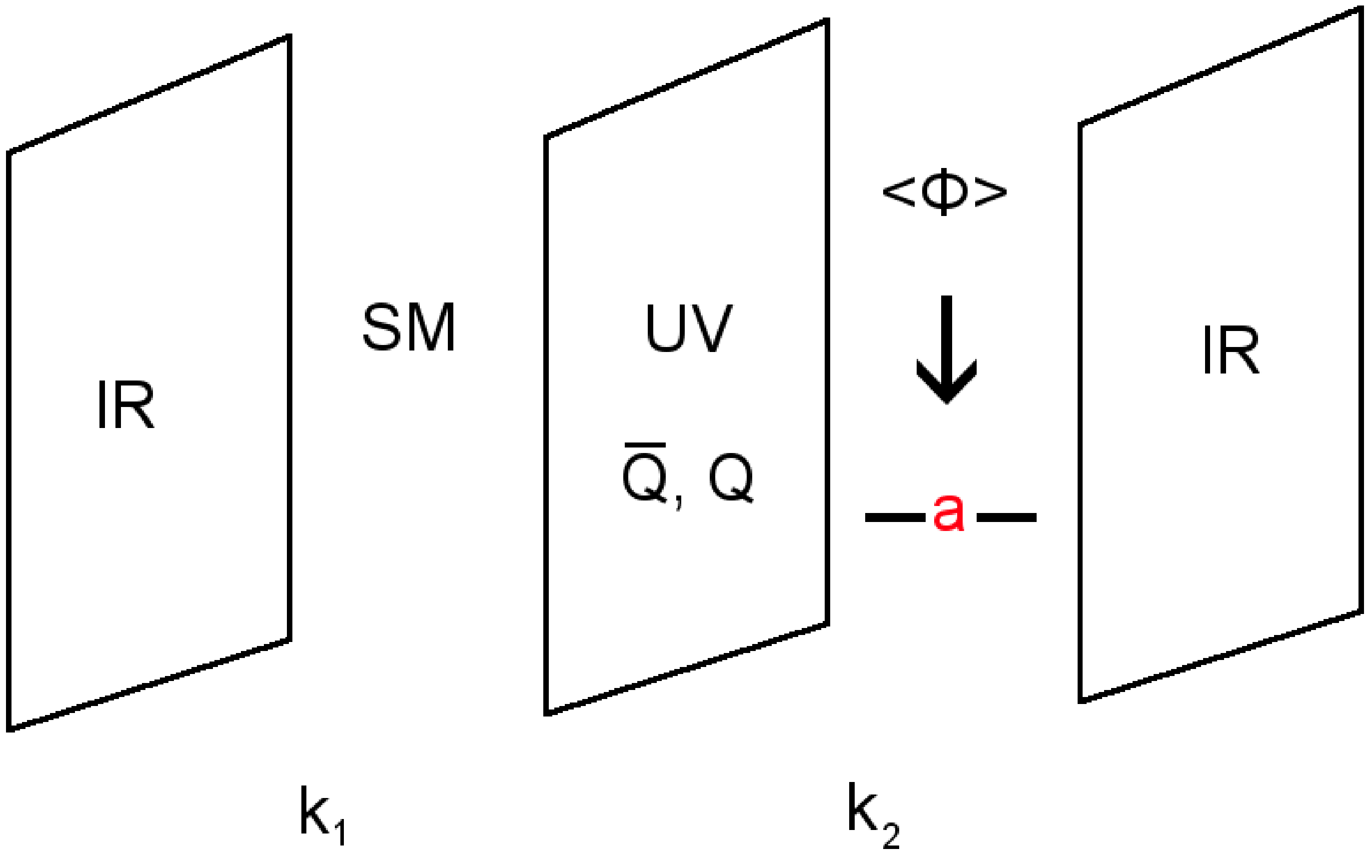
- Randall and Sundrum (PRL.83:3370-3373,1999): Large hierarchies in energy scales can be realized by compactification on AdS_5:
  - $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \equiv (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$
- The M_{EW}/M_{Pl} hierarchy is explained through an exponential 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.
- RS-type models are possible (parts of) low-energy realizations of flux compactified string theories.

RS-type models and multi-throats

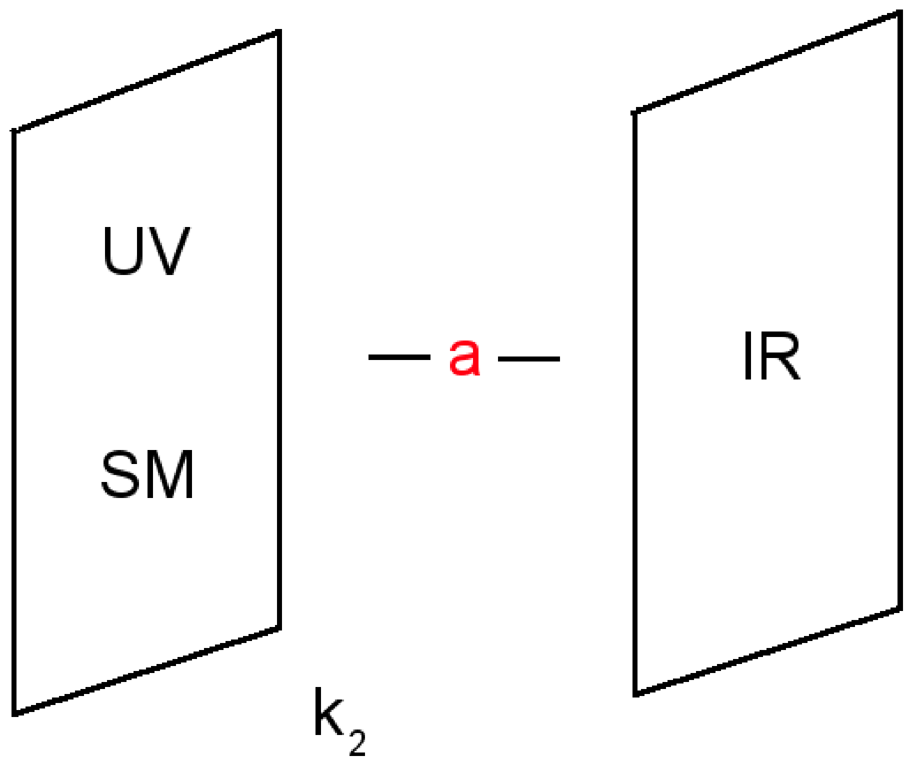
from: Cacciapaglia, Csaki, Grojean, Terning, Phys.Rev.D74:045019,2006



The QCD Axion in RS-type models



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 scalar

- $S_\Phi = M_5 \int d^5x \sqrt{-G} \left(G^{MN} \partial_M \Phi^* \partial_N \Phi - m^2 |\Phi|^2 \right)$
- Decompose: $\Phi = \eta \exp(ia)$
- boundary conditions:

$$\begin{aligned} \eta|_{IR} &= v & \partial_z \eta|_{UV} &= 0 \\ \partial_z a|_{IR} &= 0 & \partial_z a|_{UV} &= 0, \end{aligned}$$

- EOM for η at zero momentum yield a z-dependant profile for the $\langle \eta \rangle$ expectation value: $\langle \eta \rangle = A z^{2-\nu} + B z^{2+\nu}$, (where $\nu = (4 + m^2/k^2)^{1/2}$)
- The axion EOM allow for a flat axion zero mode (independent of ν).
- Note: The canonical normalization of the axion zero will depend on $\langle \eta \rangle$.

The QCD Axion from a scalar

Coupling to QCD:

- First assume the whole SM to be localized in the SM throat $\rightarrow$ UV brane localized coupling to QCD.
- Introduce colored fermions on the UV brane:

$$S_Q = \int d^4x \sqrt{-G_{\rm ind}|_{UV}} \left(\Phi \overline{Q}_L Q_R + \Phi^* \overline{Q}_R Q_L\right).$$

- Chiral rotation of the Q fields yields:

$$\int d^4x \frac{1}{32\pi^2 f_{PQ}} a(x, 1/k) F^a \tilde{F}^a.$$

The QCD Axion from a scalar

- f_{PQ} is determined by canonically normalizing a_0, yielding:

$$f_{PQ} = \frac{1}{kL_1}\sqrt{\frac{M_5 v^2}{(1+\nu)k}} \sim \frac{1}{kL_1}\frac{M_{\rm pl}}{\sqrt{2(1+\nu)}}$$

- If we demand $f_{PQ} \sim 10^{12}\,\mathrm{GeV}$ then we find that a warp factor at the PQ brane of $kL_1 \sim 10^6$ is necessary.
- Easily obtainable via the Goldberger-Wise mechanism. (*Cf.* $kL_1 \sim 10^{16}$ for SM throat)
- Axion-KK-mode masses are of order f_{PQ} ($\rightarrow$ no danger, no potential signals)

Problem

For the UV brane localized interaction used, $\langle\eta\rangle$ generates a mass term for the exotic, colored fermions Q_L, Q_R. Considering $\langle\eta\rangle\,|_{UV}$, their mass is of the order

$$m_Q \simeq v\left(\frac{1}{kL_1}\right)^{2+\nu}$$

For $f_{PQ} \sim 10^{12}\,\mathrm{GeV} \rightarrow m_Q < 10^{-6}\,\mathrm{GeV}$ in gross contradiction to collider constraints / SIMP constraints!

The QCD Axion from a scalar

Potential solution:

- Allow QCD (all gauge fields) to propagate in the PQ throat as well. Then, then Q_L, Q_R are not necessarily UV brane localized.
- For IR brane localized exotic quarks we find a mass:

$$m_Q \sim \frac{v}{kL_1} = f_{PQ}\sqrt{\frac{k}{M_5(1+\nu)}} \sim f_{PQ}$$

The QCD Axion from a 5D gauge field

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

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

- $A_\mu^{(0)}$ 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

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

Possible localizations:

- UV/IR brane.
- In the whole axion throat (need QCD in both throats)
  - *Cf.* K. Choi,[PRL**92**,101602] for this ansatz, but assuming all fields in the SM throat.

The QCD Axion from a 5D gauge field

For the brane localized cases, the coupling term becomes

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

Get f_{PQ} by canonical normalization of a_0:

- UV: $f_{PQ} = \frac{M_5 k L_1}{\sqrt{2kg_5^2}} \sim M_5^2 L_1 \gg M_5 \sim M_{\mathrm{pl}}$. FATAL!
- IR: $f_{PQ} = M_5/NL_1 \sim (M_5^3/k)^{1/2} \sim M_{\mathrm{pl}}$ No hierarchy!

The QCD Axion from a 5D gauge field

For the interaction in the whole bulk

$$S_{int} = \int d^5x \frac{\alpha}{64\pi^2 M_5} \epsilon^{MNPQR} F^a_{MN} F^a_{PQ} A_R,$$

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

$$f_{PQ} = \sqrt{\frac{2}{kg_5^2}} \frac{1}{L_1} \simeq \frac{M_{\rm pl}}{M_5 L_1}.$$

$f_{PQ} = 10^{12}\,\mathrm{GeV}$ 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