



The QCD Axion in RS-type models

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(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
- Experimental constraints on the 4D axion
- 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.

- QCD:

$$\mathcal{L}_{\text{QCD}} = \bar{q}(\gamma^\mu D_\mu - M)q - \frac{1}{2g^2} \text{Tr}(F_{\mu\nu} F^{\mu\nu})$$

- Effective contribution of the non-trivial QCD vacuum:

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

where $\bar{\theta} = \theta - \arg \det M_q$ is an a priori free parameter.

- QCD *predicts* CP violation!
- Empirically (neutron EDM) $\bar{\theta} \lesssim 10^{-9}$
→ fine-tuning between the θ vacuum and the phase of the quark mass matrix.



The Axion Solution in 4D

- Peccei, Quinn, Weinberg, Wilczek:
 - Promote $\bar{\theta}$ 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:

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

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



The Axion Solution in 4D

- The PQWW axion (two Higgs doublets) predicted $f_{PQ} \sim M_{EW}$. Experimentally ruled out.
- A way out (invisible axion):
Realize a from a $SU(2) \times U(1)$ singlet complex scalar and find additional field content to obtain the $U(1)_{PQ} \times SU(3)_c^2$ anomaly.
 - Kim, Shifman, Vainstein, Zakharov: use a complex scalar and heavy quarks.
 - Dine, Fischler, Srednicki, Zhitnitskii: use a complex scalar and two Higgs doublets.



Experimental constraints on the 4D axion

- Rare decays, (e.g. $K^\pm \rightarrow \pi^\pm a$), nuclear effects, etc.
- A (model dependant) $U(1)_{PQ} - U(1)_{em}^2$ anomaly induces

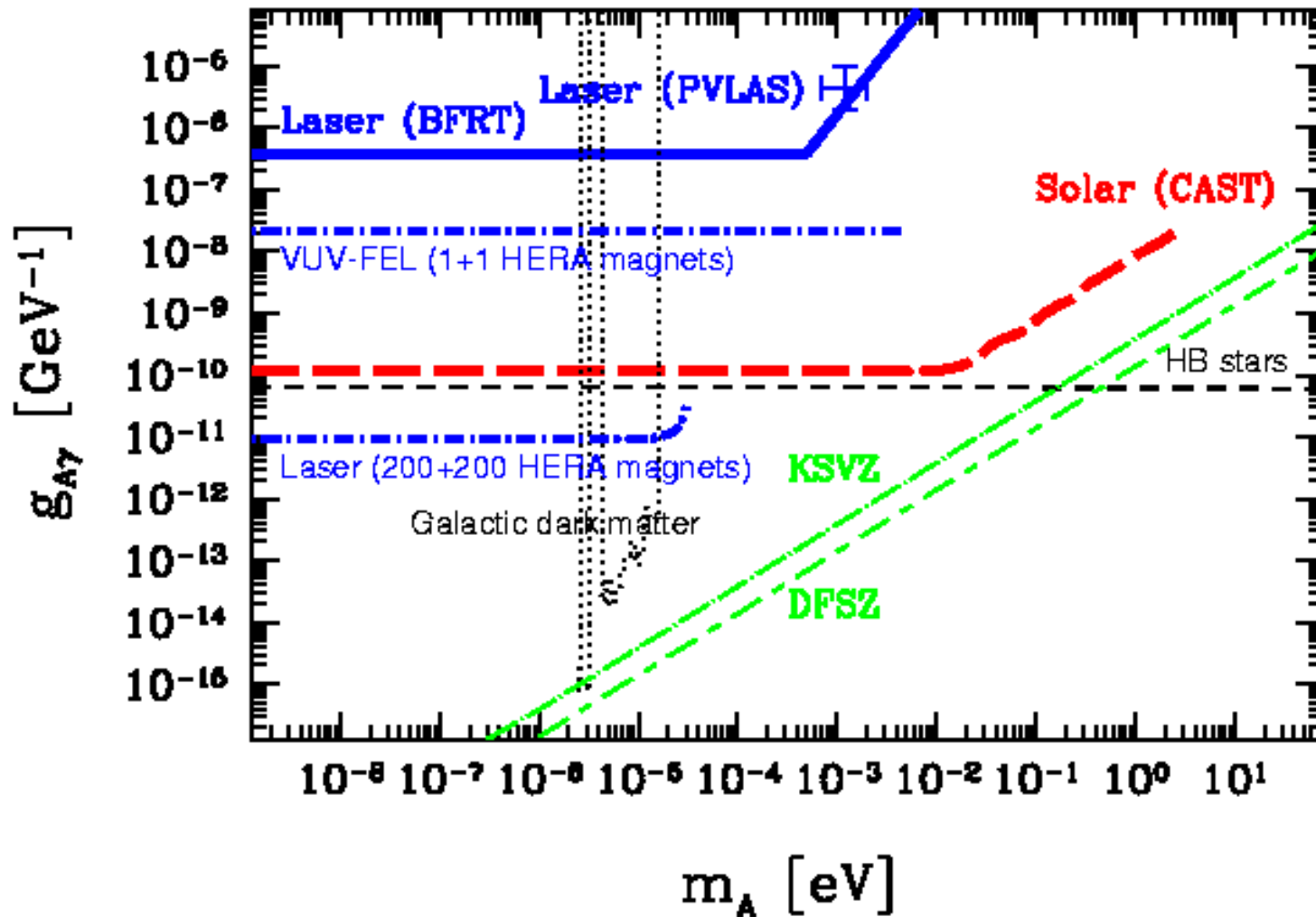
$$\mathcal{L}_a = \xi e^2 \frac{a}{32\pi^2 f_{PQ}} F_{\mu\nu}^{(em)} \tilde{F}^{(em)\mu\nu}.$$

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



Experimental constraints on the 4D axion

- Axion constraints (Ringwald hep-ph/0511184)





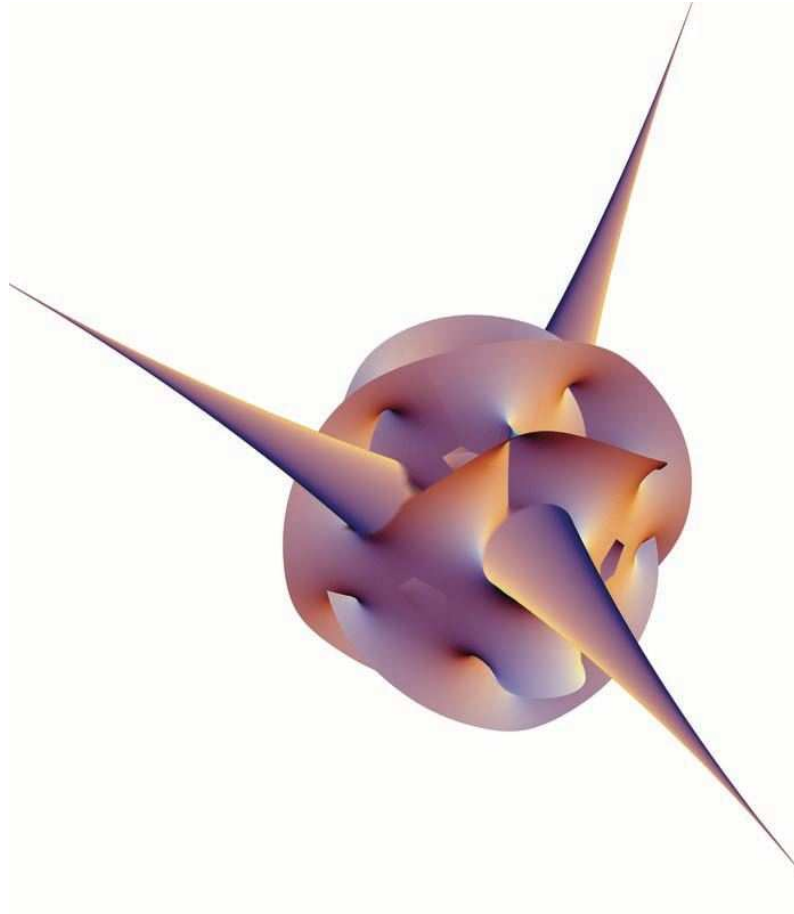
RS-type models and multi-throats

- 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





RS-type models and multi-throats

- Model the low energy approximation of such a multi-throat scenario by separate RS-type models which interact via UV boundary localized operators.
- Different scales can be realized by different AdS curvatures and/or different throat lengths.
- We use this setup to create a bottom-up toy model in order to study possibilities to realize a QCD axion with a "natural" value of f_{PQ} arising from the RS geometry.



The QCD Axion in RS-type models

- The geometry of both throats will be approximated by the standard Randall-Sundrum slice of AdS:

$$ds^2 = (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu - d^2z),$$

where their common curvature radius is $1/k$. For the first throat the coordinate lies in the range $z \in [1/k, L_1]$, while the second has coordinate w with range $w \in [1/k, L_2]$.

- $$M_{Pl}^2 = \frac{2M_5^3}{k}.$$
- We assume the usual Randall-Sundrum choice of $k \sim M_5/10$, and thus $M_5 \sim M_{Pl}/\text{few}$



The QCD Axion in RS-type models

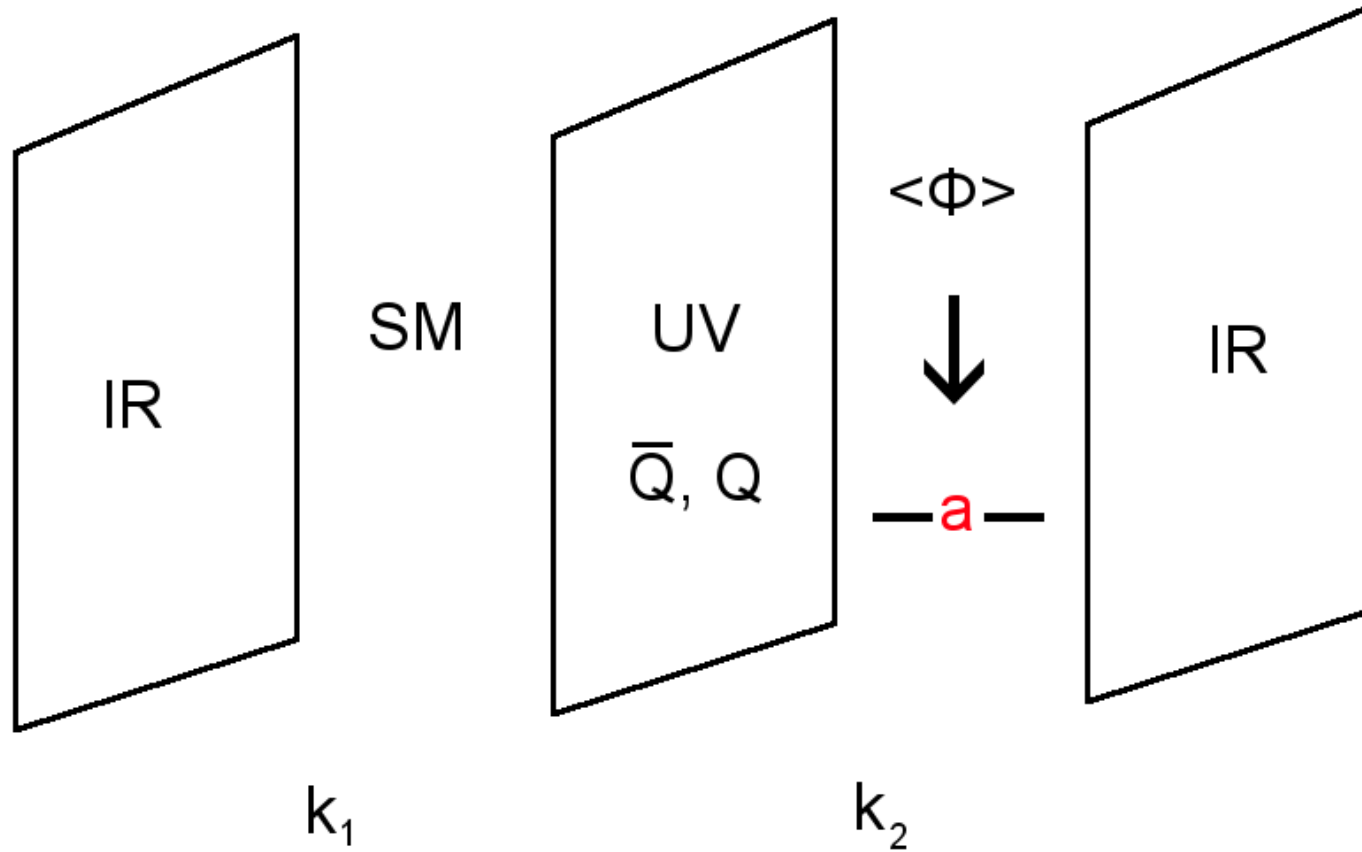
We consider two basic possibilities to obtain a pseudo-scalar from the 5D theory:

- 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.

In both realizations we consider several possibilities for the localization of the couplings.

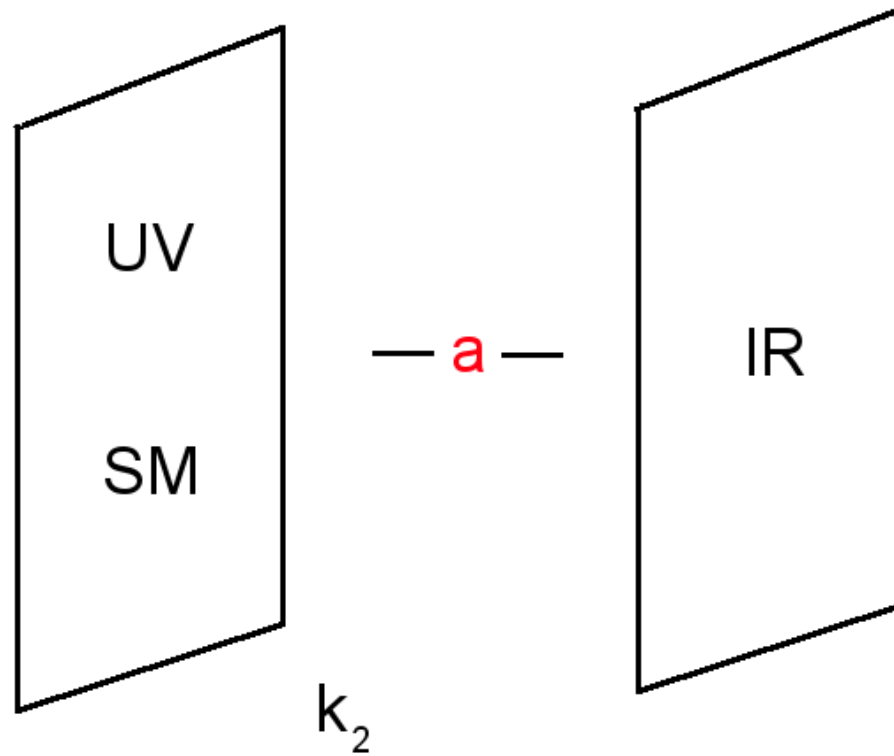


The QCD Axion in RS-type models





The QCD Axion in RS-type models





The QCD Axion from a scalar

- $S_\Phi = M_5 \int d^5x \sqrt{-G} (G^{MN} \partial_M \Phi^* \partial_N \Phi - m^2 |\Phi|^2)$
- 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:
 $\langle \eta \rangle = Az^{2-\nu} + Bz^{2+\nu}$, (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:

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

- 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:

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

- If we demand $f_{PQ} \sim 10^{12}$ 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)



The QCD Axion from a scalar

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



The QCD Axion from a scalar

Potential solutions:

- 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:

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

- (Simplest model: Take exotic quarks AND the axion field on the IR brane)



The QCD Axion from a 5D gauge field

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

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

- $A_\mu^{(0)}$ are projected out. $A_5^{(0)}$ survives
→ massless scalar degree of freedom in terms of the 4D effective theory.
- At non-zero KK-level, $A_5^{(n)}$ provide the longitudinal degrees of freedom for the massive $A_\mu^{(n)}$
→ no axion KK-modes.
- Can show that the 5D $U(1)$ gauge symmetry manifests itself in a (global) shift symmetry on $A_5^{(0)}$.



The QCD Axion from a 5D gauge field

- Solution for the $A_5^{(0)}$ profile: $A_5(x, z) = Nza(x)$
- Canonical normalization $\rightarrow N \approx \sqrt{2kg_5^2/L_1}$

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

$$\epsilon^{LMNPQ} A_L F_{MN}^a F_{PQ}^a$$

(Could arise from integrating out exotic quarks Q_L, Q_R with suitable PQ charges)

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

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

Get f_{PQ} by canonical normalization of a_0 :

- UV: $f_{PQ} = \frac{M_5 k L_1}{\sqrt{2k g_5^2}} \sim M_5^2 L_1 \gg M_5 \sim M_{pl}$. **FATAL!**
- IR: $f_{PQ} = M_5 / N L_1 \sim (M_5^3 / k)^{1/2} \sim M_{pl}$ **No hierarchy!**



The QCD Axion from a 5D gauge field

For the interaction in the whole bulk

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

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

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

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



The QCD Axion from a 5D gauge field

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



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.
- We considered IR, UV and bulk localizations for the coupling to the QCD anomaly.



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.

Multi throat setups generically offer a lot of freedom in generating scales in extra dimensional model building, but detailed implementation is more constrained by phenomenology than might be expected.