A Heterotic QCD Axion

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String Phenomenology 2015, Madrid

General Remarks

The strong CP problem.

$$\mathcal{L}_\theta = \frac{\theta}{8\pi^2} tr(F \wedge F)_{\mathrm{QCD}}$$

Naively, $\theta \simeq g_3 \simeq 1$. Experimental bounds on the electric dipole of the neutron, $\theta < 10^{-10}$

Simplest dynamical solution: PQ axion.

$$\mathcal{L}_a = \frac{a}{8\pi^2\, f_a} \mathrm{Tr}(F \wedge F)_{\mathrm{QCD}}$$

Realisation: Goldstone boson of a global $U(1)_{\mathrm{PQ}}$ with mixed anomaly and spontaneously broken at $\simeq f_a$:

$$a \to a + c$$

Astrophysical and cosmological constraints on f_a:

$$\boxed{10^9\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\mathrm{GeV}}$$

In string models: many axions available; usually $f_a \simeq 10^{16}\mathrm{GeV}$.

In heterotic compactifications the imaginary part of the dilaton multiplet

$$S = s + i\sqrt{2}\,\sigma$$

couples at tree-level to $F\tilde{F}$. The corresponding $f_\sigma \simeq M_{\mathrm{GUT}}$.
The axions coming from the T^i moduli

$$T^i = t^i + 2i\chi^i$$

couple at one loop level to $F\tilde{F}$.
Similarly, $f_{\chi^i} \simeq M_{\mathrm{GUT}}$.

Axions in Heterotic String Theory with Split Bundles

Alternative: consider heterotic CY models with bundles that (somewhere in the allowed Kähler moduli space) split as

$$\boxed{V = \bigoplus_{a=1}^{A} V_a}$$

Generically, these lead to additional Green-Schwarz anomalous $U(1)$ symmetries in 4d with D-terms of the form:

$$D_a = \frac{M_P^2}{\mathcal{V}} \epsilon \, d_{ijk} k_a{}^i t^j t^k - \sum_{I,J} q_{a,I} G_{IJ} C^I \bar{C}^J$$

where the matter fields $C^I = h^I e^{i\phi^I}$ transform as

$$\delta C^I = -i \, \eta^a \, q_{a,I} \, C^I$$

$$\delta \phi^I = -q_{a,I} \, \eta^a$$

We can construct a KSVZ axion (heavy quark axion) if there exists an exotic vector-like quark pair that couples to a singlet fields C,

$$W = \lambda \mathcal{Q} \, C \, \widetilde{\mathcal{Q}} + W_{\rm sing} + \ldots \ ,$$

At low energies, ϕ couples to $F\tilde{F}$, with

$$f = \sqrt{2} h \, .$$

The value of h in the supersymmetric vacuum is controlled by the D-term equation

$$D = \frac{M_P^2}{\mathcal{V}} \, \epsilon \, d_{ijk} \, k^i \, t^j \, t^k - q \, h^2 = 0 \ ,$$

The FI term vanishes at the split locus and can assume arbitrarily small values close to it.

Heterotic Line Bundle Models with QCD Axions

An explicit example:

Required data: (X, V) and (Γ, ϕ), $\mathcal{W}$.

$$X = \begin{array}{c} \mathbb{CP}^1 \\ \mathbb{CP}^1 \\ \mathbb{CP}^1 \\ \mathbb{CP}^1 \\ \mathbb{CP}^1 \end{array} \left[\begin{array}{cc} 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 0 & 2 \end{array} \right]^{5,45}_{-80}$$

$\Gamma = \mathbb{Z}_2 \times \mathbb{Z}_2$. Action given by:

$$g_1 : \; x_{m,\alpha} \mapsto (-1)^{\alpha} x_{m,\alpha}$$
$$g_2 : \; x_{m,\alpha} \mapsto x_{m,\alpha+1}$$
$$g_1 : \; p_\beta \mapsto (-1)^{\beta} p_\beta$$
$$g_2 : \; p_\beta \mapsto (-1)^{\beta+1} p_\beta$$

Result: quotient manifold $\widetilde{X} = X/\Gamma$ with $\pi_1(\widetilde{X}) \cong \Gamma$, $h^{1,1}(\widetilde{X}) = 5$ and $h^{2,1}(\widetilde{X}) = 15$.

$$V = \bigoplus_{a=1}^{5} \mathcal{L}_a = \bigoplus_{a=1}^{5} \mathcal{O}_X(\mathbf{k}_a)$$

explicitly given by

$$({k^i}_a) = \begin{bmatrix} -2 & 1 & 1 & 0 & 0 \\ 1 & -2 & 0 & 1 & 0 \\ 0 & 1 & -2 & 0 & 1 \\ 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & -1 \end{bmatrix} .$$

Properties: $c_1(V) = 0$, structure group $S(U(1)^5 \subset SU(5))$. $\chi(V) = -12$. Anomaly cancellation condition and stability also satisfied.

GUT group: $SU(5) \times S(U(1)^5)$.

Choice for the equivariant structure:

$$\mathcal{L}_1^{(0,1)} \oplus \mathcal{L}_2^{(0,0)} \oplus \mathcal{L}_3^{(0,0)} \oplus \mathcal{L}_4^{(0,0)} \oplus \mathcal{L}_5^{(0,0)} .$$

Heterotic Line Bundle Models with QCD Axions

multiplet	$S(U(1)^5)$ charge	bundle	cohomology
$\mathbf{10}_a$	$\mathbf{e}_a$	V_a	$H^1(X, V_a)$
$\overline{\mathbf{10}}_a$	$-\mathbf{e}_a$	V_a^*	$H^1(X, V_a^*)$
$\overline{\mathbf{5}}_{a,b}$	$\mathbf{e}_a + \mathbf{e}_b$	$V_a \otimes V_b$	$H^1(X, V_a \otimes V_b)$
$\mathbf{5}_{a,b}$	$-\mathbf{e}_a - \mathbf{e}_b$	$V_a^* \otimes V_b^*$	$H^1(X, V_a^* \otimes V_b^*)$
$\mathbf{1}_{a,b}$	$\mathbf{e}_a - \mathbf{e}_b$	$V_a \otimes V_b^*$	$H^1(X, V_a \otimes V_b^*)$

After quotienting: MSSM spectrum with a vector-like pair of quarks and singlets:

$$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_3,\ \overline{\mathbf{5}}_{1,3},\ \overline{\mathbf{5}}_{1,5},\ \overline{\mathbf{5}}_{3,4},$$

$$T_{1,4},\ \overline{T}_{1,4},\ H_{4,5},\ \bar{H}_{4,5},\ 3\,\mathbf{1}_{1,3},\ \mathbf{1}_{1,4},\ \mathbf{1}_{4,1},\ \mathbf{1}_{1,5},\ 4\,\mathbf{1}_{2,4},\ \mathbf{1}_{2,5},\ 3\,\mathbf{1}_{3,2},\ \mathbf{1}_{3,4},\ 3\,\mathbf{1}_{3,5}\ ,$$

Heterotic Line Bundle Models with QCD Axions

The $U(1)-$charges constrain the allowed superpotential operators. Importantly,

$$W \supset \overline{T}_{1,4}\, d_{3,4}\, S_{1,3}\ .$$

For $\langle S_{1,3}\rangle \neq 0$, this removes the pair $d_{3,4} - \overline{T}_{1,4}$ from the massless spectrum.

$d_{3,4}$, $\overline{T}_{1,4}$ play the role of the exotic quark fields $\mathcal{Q}$ and $\widetilde{\mathcal{Q}}$. The "missing" d-type quark is replaced by $T_{1,4}$.

If $\langle S_{1,3}\rangle$ can be stabilised at a small value, $10^{-7} \lesssim \langle S_{1,3}\rangle \lesssim 10^{-4}$ in GUT units, the axion coupling parameter will be in the phenomenologically allowed range.

Conclusions

Heterotic CY models with split bundles can accommodate all the required ingredients for a successful axion model:

- Green-Schwarz anomalous $U(1)$ symmetries with associated FI terms that vanish at specify loci in Kähler moduli space;
- SM multiplets, additional singlet matter fields and vector-like pairs of exotic quarks, charged under the extra $U(1)$ symmetries;
- trilinear superpotential coupling $\mathcal{Q}C\tilde{\mathcal{Q}}$; $C = he^{i\phi}$
- axion coupling parameter controlled by the FI term can be arbitrarily small close to the split locus.

Thank you!