Modification of Decay Constants of Superstring Axions

work with Jihn E. Kim
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Ian-Woo Kim
Seoul National University

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- One of the most puzzling problems of Standard Model is strong CP problem.

  Invisible axion with PQ scale $10^9~\mathrm{GeV} \leq F_a \leq 10^{12}~\mathrm{GeV}$ is the most attractive solution for strong CP problem.

- Superstring theories provide axion candidates in B_{MN} : MI-axion, MD-axion.

  However, for string theoretic axions, the decay constants take values of $\mathcal{O}(M_{\rm st})$.

- Our prime objective is to find out mechanisms of lowering axion decay constants.

  To have a large hierarchy of axion decay constants, a warped background is effective for some localized MD-axions.

- Even with lowering axion decay constant, axion mixing effect may lead QCD axion to have $\mathcal{O}(M_{\rm st})$ decay constant.

  We suggest that the moderate scale difference between $\Lambda_{\rm gaugino}$ and $\Lambda_{\rm flavor}$ mitigate this axion mixing problem.

Strong CP problem and QCD Axion

- QCD has θ term :

  $$\frac{\theta}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} \longrightarrow \text{ CP violating interaction } .$$

  leads to electric dipole moment of n and e.

  $$|\theta| < \mathcal{O}\left(10^{-10}\right)$$

- Axion is a dynamical θ field.

  $$\mathcal{L} = -\frac{1}{4g^2} F^a F^a + \frac{1}{2} |\partial_\mu a|^2 + \sum_i \bar{q}_i (i\not{D} - m_i) q_i + \frac{a}{32\pi^2 F_a} F^a \tilde{F}^a + \frac{\theta'}{32\pi^2} F^a \tilde{F}^a$$

  The pseudo-Goldstone boson of PQ symmetry acquire mass from QCD instanton effects.

  $\longrightarrow$ Dynamical Relaxation of θ parameter occurs!

- PQ scale F_a is subject to astrophysical constraints:
  - Window of Axion Decay Constant:

    $$10^9 \text{ GeV} \leq F_a \leq 10^{12} \text{ GeV}$$

    Lower bound from too rapid supernova cooling.
    Upper bound from too much axion dark matter.

Axions in Heterotic String Theory

- In heterotic string theories, axions appear in anti-symmetric tensor B_{MN} .
- MI-Axion $B_{\mu\nu}$: μ, ν tangent to 4D spacetime.

  3-form flux $H_{\mu\nu\rho} = M\epsilon_{\mu\nu\rho\sigma}\partial^\sigma a$ (M:decay constant) satisfies model independent Bianchi identity:

$$dH = -\frac{1}{30} TrF^2 + \dots$$

  $\rightarrow$ Axion decay constant is $\mathcal{O}(10^{16}\ \mathrm{GeV})$. $\longrightarrow$ Harmful axion!
- MD-Axion B_{ij} : i, j in internal direction.

  MD-Axions couple to field strengths via the Green-Schwarz term

$$\int B \wedge F \wedge F \wedge \langle F \rangle \wedge \langle F \rangle + \dots .$$

- Depending on the way B_{ij} is embedded in the internal space, MD-axions can be localized.
  - Harmonic 2-forms ω_i are the zero mode wavefuncions of B_{ij}.

  $\rightarrow$ The Hodge-Betti number $b_{(1,1)}$ corresponds to the number of MD-axions.
  - By de Rham's theorem, $\exists$ 2-cycle C_i for each harmonic 2-form ω_i s.t.

$$\int_{C_i} \omega_i = 1, \quad \int_{C_i} \omega_j = 0 \text{ for } i \neq j.$$

  $\rightarrow$ The wave function has the largest value on the smallest cycle in the same homology class.

- Thus, MD-axions can be localized at a nearly vanishing 2-cycle , such as at the fixed point of the orbifold compactification or its blown-up cycle.

Warped Geometry in Flux Compactification

- The localized gravity can scale down all the dynamical scale of the localized fields at warped region.
- In string theories, supersymmetric flux compactification yields warped geometry.
- In heterotic strings, H_{MNP} is the only flux we can turn on.
  - Strominger (1986) obtained conditions for supersymmetric heterotic flux manifold: complex, non-Kähler torsional constraints, conformally balanced holomorphic 3-form and Hermitian YM condition.
    The metric in the Einstein frame is

    $$ds_E^2 = e^{-\phi(y)/2} ds_{4D}^2(x) + ds_{6D}^2(y)$$

  - Recently, Becker *et al.* constructed non-singular heterotic flux solution in which 6D internal manifold is $K3$-based $T2$-bundle.

$$\begin{aligned} ds_E^2 = & e^{-\phi(y)/2} ds_{4D}^2(x) \\ & + e^{-\phi(y)/2}((dx+\alpha_1)^2 + (dy+\alpha_2)^2) + e^{3\phi(y)/2} ds_{K3}^2 \end{aligned}$$

- One example : Orbifold limit of trivial T2-bundle with the vector bundle satisfying $\mathrm{tr}\ R_{ab}R^{ab} = \frac{1}{30}\mathrm{tr}\ F_{ab}F^{ab}$
  - We have the geometry

$$ds_E^2 = \Delta^{-1/2}(\eta_{\mu\nu}dx^\mu dx^\nu) + \Delta^{-1/2}\left((dx+\alpha_1)^2 + (dy+\alpha_2)^2\right) + \Delta^{3/2}ds_{\mathrm{K3}}^2.$$

where

$$\Delta^2 = c_0 + Az^1 + Bz^2 + \mathrm{c.c.}, \qquad \text{with } \Delta = e^\phi,$$
$$H = Adz^1 \wedge dz^2 \wedge d\bar{z}^2 + Bdz^1 \wedge d\bar{z}^1 \wedge dz^2 + \mathrm{c.c.}$$

→ Localized MD-axion appears with power-law warp factor at the fixed point region $z^1 = z^2 = 0$ for $c_0 \ll Az^1 + Bz^2$!

! Note that this cannot break SUSY to $N_{4D} = 1$. To examine more realistic cases, the nontrivial T2-bundle with non-standard bundle structure must be considered.

→ The possibility of existence of exponentially warped throat is still open.

With localized axion in highly warped region, the scale of axion decay constant can be lowered.

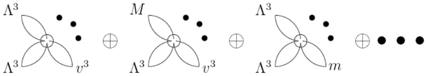
Axion Mixing Effect

- Even with the lowered MD-axion decay constant, QCD axion at the intermediate scale is not automatic due to MI-axion at GUT scale.
  - To be QCD axion, MD-axion must have coupling with QCD. MI-axion has couplings with all the gauge group universally, especially QCD and the hidden sector which has relevance to SUSY breaking.
  - Gravity mediated scenario $\Lambda_{\rm hid} \approx 10^{13}{\rm GeV}$
  - Axion potential:

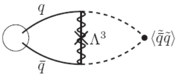
$$
\begin{aligned}
V \quad \sim \quad & -V_{\rm hid} \cos\left(\alpha_{MI}\frac{a_{MI}}{F_{MI}} + \alpha_{MD}\frac{a_{MD}}{F_{MD}}\right) \\
& -V_{\rm QCD} \cos\left(\beta_{MI}\frac{a_{MI}}{F_{MI}} + \beta_{MD}\frac{a_{MD}}{F_{MD}} + \dots\right)
\end{aligned}
$$

  if $V_{\rm hid} \gg V_{\rm QCD}$, the massive axion becomes $\alpha_{MI}\frac{a_{MI}}{F_{MI}} + \alpha_{MD}\frac{a_{MD}}{F_{MD}} \propto \frac{a'}{F'}$ where $F' \sim \min(F_{MI}, F_{MD})$. Then, QCD axion is orthogonal to this axion so that the larger F is chosen.

- Naively, it seems that we have to lower the DSB scale Λ_{hid} of hidden sector than Λ_{QCD}.
- But, SUSY can help this part.
  - Instanton contribution to the scalar potential:



  - To give the axion potential at least one fermion mass term must be involved. (Instanton potential terms involving only condensations lead to η' masses.)
  - For gaugino, gaugino mass $\sim \mathcal{O}(\mathrm{GeV})$ suppression.
  - Hidden-sectors quark cannot have direct contraction due to SUSY. Their contraction can be understood as



$\longrightarrow$ can be suppressed by $M\Lambda^3 \left(\frac{\langle\bar{\tilde{q}}\tilde{q}\rangle}{8\pi^2\Lambda^2}\right)^n$ for n-hidden sector quarks.

Conclusion

- In Heterotic string theory, MI-axion has universal model-independent axion decay constant scale.
- MD-axion can be localized at a nearly vanishing 2-cycle. With appropriate flux compactification, localized axion can have warp-factor-suppressed decay constant.
- Due to hidden sector dynamics and axion mixing effect, we must lower hidden sector contribution to the axion instanton potential to have QCD axion with the intermediate scale decay constant.
- We suggest that several hidden sector quarks with chiral symmetry breaking scale somewhat lower than the confining scale can make the axion potential significantly lowered.