String Axiverse with Moduli Stabilization

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KC, K.S. Jeong, K.-I. Okumura, M. Yamaguchi, arXiv:1104.3274
KC & K.S. Jeong, arXiv:1210.xxxx (to appear)

String axiverse

4D effective theory of string theory involves a plenty of axions which may include the QCD axion solving the strong CP problem.

* p-form gauge fields in 10D spacetime:

$$C_{[M_1 M_2 .. M_p]} \quad (p = 2, 3, ...)$$

* Compactified 6D internal space, e.g. CY space, involving a multiple number of p-dim cycles σ_I:

$\Rightarrow$ 4D axion fluctuations which are massless in perturbation theory:

$$C_{[m_1 m_2 .. m_p]}(x, y) = \sum_I a_I(x) \omega^I_{[m_1 m_2 .. m_p]}(y)$$

$$\left(x^\mu = \text{4D coordinates}, \quad y^m = \text{6D coordinates} \right)$$

$$d\omega^I = 0, \quad \int_{\sigma_I} \omega^J = \delta_I^J$$

Generically, these axions can couple to the QCD anomaly,

$$\int C\wedge G\wedge G\wedge ... \quad \Rightarrow \quad \int d^4x \sum_I c_I a_I \, G^{\mu\nu}\tilde{G}_{\mu\nu} \quad \left(c_I = \int \omega_I \wedge ... \right),$$

and also get a mass from high scale non-perturbative effects such as stringy instantons or hidden gaugino condensations.

* Some axions can be heavy:

$$m_{a_H} \gtrsim \mathcal{O}(m_{3/2})$$

* There can be a QCD axion combination which gets a mass dominantly from the QCD anomaly:

$$m_{a_{QCD}} \sim f_\pi m_\pi / f_{a_{QCD}}$$

* The remained axion combinations can be ultralight:

$$m_{a_L}^2 \sim \epsilon_0 e^{-S_{\rm ins}} m_{3/2}^N M_{\rm string}^{4-N} / f_{a_L}^2$$

$$\left(S_{\rm ins} = \text{ Instanton action} \gg 1, \quad \epsilon_0 = \text{ Zero mode factor} \ll 1 \right)$$

Axion scale (= axion decay constant):

Axion Superfield: $T = t + ia + \sqrt{2}\theta\tilde{a} + \theta^2 F^T$

$$\big(\text{Modulus partner } t \propto \text{Vol}(p\text{-cycle})\big)$$

$$\mathcal{L}_{\text{axion}} = M_{\text{Pl}}^2 \frac{\partial^2 K}{\partial t^2} \partial_\mu a \partial^\mu a + \frac{n}{4} a G\tilde{G} + \ldots \qquad \left(a \equiv a + \frac{1}{4\pi}\right)$$

$$\Rightarrow \qquad f_a = \sqrt{\frac{\partial^2 K}{\partial t^2}} \frac{M_{\text{Pl}}}{8\pi^2} \sim 3\sqrt{\frac{\partial^2 K}{\partial t^2}} \times 10^{16}\ \text{GeV},$$

In models with high compactification scale, e.g.

$$M_{\text{com}} \sim M_{GUT} \sim 2 \times 10^{16}\ \text{GeV},$$

typically we have

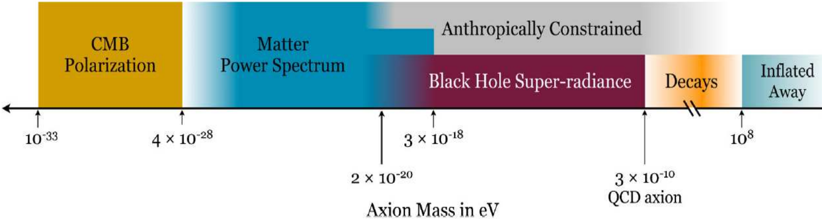
$$\frac{\partial^2 K}{\partial t^2} \sim \frac{1}{t^2} \sim g_{GUT}^4 \quad \Rightarrow \quad f_a \sim 10^{16}\ \text{GeV}.$$

KC & Kim(1985); Svrcek & Witten(2006)

Based on these observations, recently various cosmological or astrophysical implications of ultralight axions in string axiverse have been studied under the assumption that all light axions have a similar decay constant:

$$f_a \sim 10^{16}\ \mathrm{GeV}.$$

Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March−Russell(2010)



There are many issues about string axiverse, which need to be clarified more carefully:

* Cosmological moduli and gravitino problem

* Possible existence of a QCD axion and its decay constant

* Possible existence of ultralight axions and their decay constants

* Possibility of axino dark matter

* Implication for SUSY breaking and its mediation:

$$\int d^2\theta \frac{1}{32\pi^2 f_a} A W^\alpha W_\alpha \quad \left(A = s + ia + \theta\tilde{a} + \theta^2 F^A\right)$$

$$\Rightarrow \quad \delta M_{1/2} \sim \frac{F^A}{8\pi^2 f_a}$$

All these issues should be addressed with a concrete scheme of moduli stabilization.

Bobkov,Braun,Kumar,Raby(2010); Acharya,Bobkov,Kumar(2010); Cicoli,Goodsell,Ringwald(2012)

QCD axion scale:

Cosmological QCD axion mass density:

$$\Omega_a h^2 \sim 0.1 \left(\frac{f_{a_{QCD}}}{3 \times 10^{11}\ \mathrm{GeV}} \right)^{7/6} \delta\theta^2$$

$$\Rightarrow \quad f_{a_{QCD}} \lesssim 3 \times 10^{11} \delta\theta^{-12/7}\ \mathrm{GeV}$$

It is in principle possible that $f_{a_{QCD}} \sim 10^{16}$ GeV is cosmologically viable with a small axion misalignment $\delta\theta \sim 10^{-3}$ (or with a late entropy production after the QCD phase transition), which might be justified by anthrophic argument.

Linde(1988); Tegmark,Aguirre,Rees,Wilczek(2006)

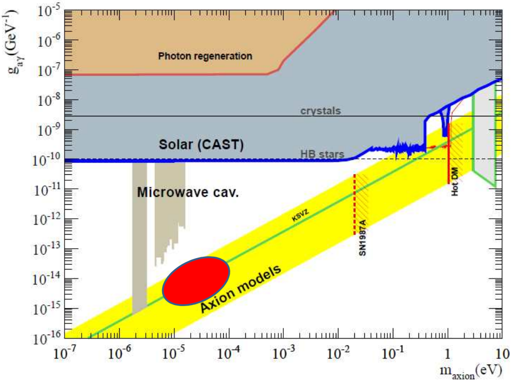
However it will be much more interesting if string axiverse accommodates a QCD axion with

$$f_{a_{QCD}} \sim 10^{11} - 10^{12}\ \mathrm{GeV}.$$

Such QCD axion with $f_{a_{QCD}} \sim 10^{11} - 10^{12}$ GeV gives the correct dark matter density for $\delta\theta = \mathcal{O}(1)$, and might be able to be detected in near future!

$$m_a \sim 2 \times 10^{-5} \left(\frac{3 \times 10^{11}\ \text{GeV}}{f_{a_{QCD}}} \right) \text{eV}$$

$$g_{a\gamma} \sim 3 \times 10^{-15} \left(\frac{3 \times 10^{11}\ \text{GeV}}{f_{a_{QCD}}} \right) \text{GeV}^{-1}$$



In fact, there are several ways to have $f_{a_{QCD}} \ll 10^{16}$ GeV in string theory.

For instance, the p-cycle σ for the QCD axion might be a small cycle embedded in large bulk volume (Large Volume Scenario), or might be located at a highly warped region in the internal space (Warped Compactification):

$$\frac{\partial^2 K}{\partial t^2} \sim \frac{1}{\text{large bulk volume}} \quad \text{Cicoli,Goodsell,Ringwald(2012)}$$
$$\left(\text{or small warp factor}\right)$$

$$\Rightarrow \quad f_a = \sqrt{\frac{\partial^2 K}{\partial t^2}} \frac{M_{\rm PL}}{8\pi^2} \ll 10^{16}\ \text{GeV}.$$

However in such schemes, $M_{\rm GUT}$ is also similarly red-shifted, making it difficult to have $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV.

On the other hand, in models with anomalous $U(1)$ gauge symmetry with small (vanishing in SUSY limit) FI term, the QCD axion scale can be lowered down to $f_{a_{QCD}} \ll 10^{16}$ GeV, without affecting $M_{\rm GUT} \sim 10^{16}$ GeV. KC,Jeong,Okumura,Yamaguchi(2011)

Anomalous $U(1)_A$ gauge symmetry with $U(1)_A$-$SU(3)_c$-$SU(3)_c$ anomaly cancelled by the GS mechanism:

$$A_\mu \to A_\mu + \partial_\mu \alpha(x), \quad X_i \to e^{iq_i\alpha(x)} X_i, \quad a \to a + \delta_{\rm GS}\alpha(x)$$

$$C_{[m_1 m_2 .. m_p]}(x,y) = a(x)\omega_{[m_1 m_2 .. m_p]}(y)$$

$$\delta_{\rm GS} = \frac{1}{8\pi^2}\sum_i q_i {\rm Tr}(T_a^2(X_i)) \;\; \text{for} \;\; a \equiv a + \frac{1}{4\pi}$$

$$\begin{aligned} \mathcal{L}_{\rm eff} &= M_{\rm Pl}^2 \frac{\partial^2 K}{\partial t^2}\left(\partial_\mu a - \delta_{\rm GS} A_\mu\right)^2 + \frac{1}{4} a G\tilde{G} \\ &+ D_\mu X_i^* D^\mu X_i - \frac{g_A^2}{2}\left(\delta_{\rm GS} M_{\rm Pl}^2 \frac{\partial K}{\partial t} - \sum_i q_i |X_i|^2\right)^2 + \ldots \end{aligned}$$

$$(\, t = \text{modulus partner of } \; a \,)$$

To be phenomenologically viable, some $U(1)_A$ charged scalar field X should have a nonzero VEV $\langle X \rangle \gtrsim 10^{10}$ GeV.

Then there are two axion-like fields, a and $\mathrm{Arg}(X)$, and the physical QCD axion is given by the $U(1)_A$ invariant combination:

$$a_{QCD} \propto a + \frac{q_X}{\delta_{\rm GS}} \mathrm{Arg}(X),$$

while the other combination becomes the longitudinal component of the $U(1)_A$ gauge boson A_μ.

There are two (modulus-dependent) mass scales in the theory:

$$\text{FI-term}: \ \xi_{FI}(t) = \delta_{\rm GS} M_{\rm Pl}^2 \frac{\partial K}{\partial t},$$

$$\text{Stückelberg mass}: \ M_{ST}^2(t) = \delta_{\rm GS}^2 M_{\rm Pl}^2 \frac{\partial^2 K}{\partial t^2},$$

which will determine the two observable mass scales:

$U(1)_A$ gauge boson mass, QCD axion scale

$$\mathcal{L}_{\text{eff}} = \frac{M_{ST}^2}{\delta_{GS}^2}\left(\partial_\mu a - \delta_{\text{GS}} A_\mu\right)^2 + \frac{1}{4} a G\tilde{G}$$
$$+ \quad D_\mu X_i^* D^\mu X_i - \frac{g_A^2}{2}\left(\xi_{FI} - \sum_i q_i |X_i|^2\right)^2 + \ldots$$

* D-flat condition:

$$D_A = \xi_{FI} - q_X |X|^2 = 0 \quad \rightarrow \quad |X| \sim \sqrt{\xi_{FI}(t)}$$

* $U(1)_A$ gauge boson mass:

$$M_A = \sqrt{M_{ST}^2 + q_X^2 |X|^2} \sim \text{Max}\,(|X|,\, M_{ST})$$

* QCD axion scale:

$$f_{a_{QCD}} = \frac{|X| M_{ST}}{\sqrt{M_{ST}^2 + |X|^2}} \sim \text{Min}\,(|X|,\, M_{ST})$$

In models with $M_{\rm GUT} \sim 10^{16}$ GeV,

$$M_{ST} = \delta_{\rm GS} M_{\rm Pl} \sqrt{\frac{\partial^2 K}{\partial t^2}} \sim 10^{16}\ \text{GeV} \quad \left(\delta_{\rm GS} = \mathcal{O}\left(\frac{1}{8\pi^2}\right)\right)$$

On the other hand, most of the potentially (semi)realistic *D*-brane models realized in type IIB or IIA string theory admit a vacuum solution with

$$\xi_{FI} = \delta_{\rm GS} M_{\rm Pl}^2 \frac{\partial K}{\partial t} = 0 \ \ \text{(in SUSY limit with } X_i = 0\text{)},$$

which can be shifted to a local SUSY-breaking minimum with

$$\sqrt{\xi_{FI}} \sim |X| \sim f_{a_{QCD}} \ll 10^{16}\ \text{GeV},$$

once SUSY breaking effects are taken into account.

(Such vacuum configuration is possible also in heterotic string theory with stability wall. Anderson,Gray,Lukas,Ovrut(2009))

In case with multiple light axions which couple to the QCD anomaly:

KC &Kim(1985)

$$\mathcal{L}_{\rm axion} = \frac{1}{2}(\partial a_1)^2 + \frac{1}{2}(\partial a_2)^2 + \frac{1}{32\pi^2}\left(\frac{a_1}{f_1} + \frac{a_2}{f_2}\right) G\tilde{G}$$

$$a_{QCD} = \frac{f_2 a_1 + f_1 a_2}{\sqrt{f_1^2 + f_2^2}}, \qquad f_{a_{QCD}} = \frac{f_1 f_2}{\sqrt{f_1^2 + f_2^2}} \sim \text{Min}\,(f_1, f_2)$$

$$a_L = \frac{f_1 a_1 - f_2 a_2}{\sqrt{f_1^2 + f_2^2}}, \qquad f_{a_L} = \sqrt{f_1^2 + f_2^2} \sim \text{Max}\,(f_1, f_2)$$

KKLT axiverse KC & Jeong(2012)

Most of the physical issues about string axiverse, e.g. axion scales, axion, moduli, and axino masses, SUSY breaking and its mediation, should be addressed with a concrete scheme of moduli stabilization.

Here I am going to present a scheme, which is a generalization of the KKLT moduli stabilization, realizing an axiverse scenario with

1) $M_{\rm GUT} \sim 10^{16}$ GeV

2) QCD axion with $f_a = \mathcal{O}(10^{10} - 10^{12})$ GeV

3) Ultralight axions with $f_a \sim 10^{16}$ and/or $f_a \ll 10^{16}$ GeV

4) All moduli are heavy enough to avoid the cosmological moduli problem

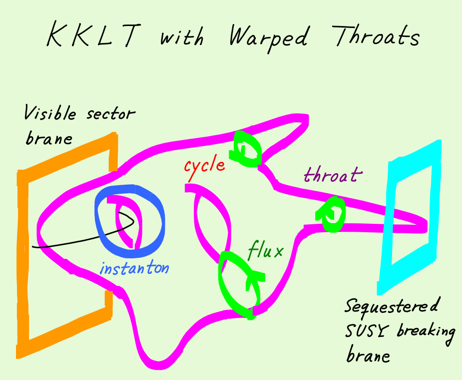
5) Deflected mirage mediation of SUSY breaking:

Moduli mediation $\sim$ Anomaly mediation $\sim$ Gauge mediation

Everett,Kim,Ouyang,Zurek(2008); KC,Jeong,Nakamura,Okumura,Yamaguchi(2009)

KKLT moduli stabilization

- Flux stabilization of complex structure moduli and dilaton
- Non-perturbative stabilization of (some of) Kähler moduli by instanton-induced superpotential or hidden gaugino condensation
- Sequestered SUSY-breaking at the tip of throat



KKLT Axiverse: KC & Jeong(2012)

Generic string compactification involving

* many Kähler moduli

$$\{T_I\} \quad \Big(I = 1, 2, .., N;\ N = \mathcal{O}(10 - 100)\Big)$$

* anomalous $U(1)_A$ gauge symmetries which admit

$$\xi_{FI} = 0 \quad \text{in SUSY limit.}$$

For such $U(1)_A$ symmetries, their vector superfields V_A get a superheavy mass:

$$M_{V_A} \sim M_{ST} \sim \delta_{GS} M_{\rm Pl} \sim 10^{16}\ \text{GeV}$$

by absorbing some Kähler moduli $\{T_A\}$.

$\Rightarrow$ Supersymmetric Stückelberg mechanism or D-term stabilization of $\{T_A\}$

After these massive V_A are integrated out, low energy effective theory includes three sectors:

i) Kähler moduli $\{T_M\}$ not absorbed into V_A $\left(\{T_I\} = \{T_M, T_A\}\right)$

ii) PQ sector $\{X_i\}$ which break the global part of $U(1)_A$ spontaneously at scales $\ll M_{ST}$,

iii) the MSSM sector.

We then have two different types of potentially light axions:

* Kähler axions $a_M = \text{Im}(T_M)$ with $f_a \sim 10^{16}$ GeV

* Open string axions $\text{Arg}(X_i)$ with $f_a \sim \langle X_i \rangle \ll 10^{16}$ GeV

The Kähler moduli $\{T_M\}$ can be further splitted into two classes:

$$\{T_M\} = \{T_m, T_u\}$$

$\{T_m\}$ = Kähler moduli stabilized by $W_{\rm NP} = \sum_m A_m e^{-a_m T_m}$

$\{T_u\}$ = Other Kähler moduli with negligible $W_{\rm NP}$, which are stabilized by the uplifting potential KC & Jeong(2007)

Effective lagrangian:

$$\mathcal{L}_{\rm eff} = \int d^4\theta \left[CC^*\Omega + C^2C^{*2}\theta^2\bar{\theta}^2 P_0\right] + \int d^2\theta\, C^3 W + ...,$$

$$\Omega = -3e^{-K_0(T_M+T_M^*)/3} + Y_i(T_M+T_M^*)X_i^*X_i + Y_\alpha(T_M+T_M^*)\Phi_\alpha^*\Phi_\alpha$$

$$W = W_0 + \sum_m A_m e^{-a_m T_m} + W_{\rm PQ}(X_i) + W_{\rm MSSM}(\Phi_\alpha)$$

P_0 = Low energy remnant of sequestered SUSY breaking
= Independent of T_M.

In our scheme, we can stabilize all Kähler moduli with a Kähler potential at leading order in g_s and α' expansions, which obeys

$$K = K_0(T_I + T_I^*) + Z_\alpha(T_I + T_I^*)\Phi_\alpha^*\Phi_\alpha$$

$$K_0^{I\bar{J}}\partial_I K_0 \partial_{\bar{J}} K_0 = 3, \quad (T_I + T_I^*)\partial_I K_0 = -3, \quad K_0^{I\bar{J}}\partial_{\bar{J}} K_0 = -(T_I + T_I^*)$$

$$Z_\alpha(\lambda(T_I + T_I^*)) = \lambda^{n_\alpha} Z_\alpha(T_I + T_I^*)$$

Grimm,Louis(2004); Conlon,Cremades,Quevedo(2007)

Integrating out (V_A, T_A) with $\xi_{FI} \propto \partial_A K_0 = 0$,

$$K_{\rm eff} = K_0(T_M + T_M^*) + Z_\alpha(T_M + T_M^*)\Phi_\alpha^*\Phi_\alpha$$

$$K_0^{M\bar{N}}\partial_M K_0 \partial_{\bar{N}} K_0 = 3, \quad (T_M + T_M^*)\partial_M K_0 = -3, \quad K_0^{M\bar{N}}\partial_{\bar{N}} K_0 = -(T_M + T_M^*)$$

$$Z_\alpha(\lambda(T_M + T_M^*)) = \lambda^{n_\alpha} Z_\alpha(T_M + T_M^*)$$

No-scale property of K_0 and the scaling property of Z_α allow us to determine the structure of SUSY breaking and soft terms without knowing the explicit form of K_0 and Z_α!

Kähler Moduli stabilization: $\{T_M\} = \{T_m, T_u\}$

$T_m = t_m + ia_m$ are stabilized by the NP superpotential

$$\Delta W_{\rm NP} = \sum_m A_m e^{-a_m T_m},$$

while $t_u = {\rm Re}(T_u)$ are stabilized by the uplifting potential

$$V_{\rm lift} = P_0 e^{2K_0(T_M+T_M^*)/3} \quad \left(\langle V_{\rm lift}\rangle = 3m_{3/2}^2 M_{\rm Pl}^2\right).$$

The resulting moduli, axion and modulino masses, and the moduli F-components are independent of the form of K_0, up to small corrections suppressed by $\frac{1}{\ln(M_{\rm Pl}/m_{3/2})}$.

Kähler moduli, axion and modulino masses:

$$T_M = t_M + ia_M + \sqrt{2}\theta\tilde{T}_M + \theta^2 F^M$$

$$m_{t_m} \simeq m_{a_m} \simeq m_{\tilde{T}_m} \simeq 2m_{3/2}\ln(M_{\rm Pl}/m_{3/2})$$

$$m_{t_u} \simeq \sqrt{2}m_{3/2}, \quad m_{a_u} = 0, \quad m_{\tilde{T}_u} \simeq m_{3/2}$$

Moduli-mediated SUSY breaking:

Universal moduli F-components, although T_m and T_u are stabilized by different dynamics $\Rightarrow$ Overall volume-modulus mediation

$$\frac{F^m}{T_m + T_m^*} = \frac{F^u}{T_u + T_u^*} = \frac{m_{3/2}}{\ln(M_{\rm Pl}/m_{3/2})}$$

$\Rightarrow$ Moduli-mediated soft scalar masses and A-parameters are determined simply by the scaling weights n_α, and independent of the detailed form of the Kähler potential.

$\Rightarrow$ Gaugino masses: $M_a \sim \frac{m_{3/2}}{8\pi^2} \quad \rightarrow \quad m_{3/2} \gtrsim 40$ TeV.

1) All Kähler moduli can be heavy enough to avoid the cosmological moduli problem.
(In fact, open string saxion can trigger a late thermal inflation, which would dilute the coherent oscillation of Kähler moduli.)

2) All Kähler axions have $f_a \sim 10^{16}$ GeV, and some of them (a_u) can be ultralight:

$$\begin{aligned} m_{a_m} &\simeq 2m_{3/2}\ln(M_{\rm Pl}/m_{3/2}) \sim 10^7 \text{ GeV}, \\ m_{a_u} &\simeq 0 \end{aligned}$$

In principle, a combination of a_u can be identified as the QCD axion.

However, to identify the true QCD axion combination and determine its decay constant, we need to check if there are other light axions which couple to $G\tilde{G}$ and have lower f_a.

Open string saxion stabilization and the axion scales:

At low energy scales below $M_{ST} \sim 10^{16}$ GeV, the model has anomalous global $U(1)$ symmetries, which correspond to the global part of $U(1)_A$ gauge symmetries.

We are interested in the case that non-perturbative explicit breaking of these $U(1)$ symmetries are negligible.

Such global symmetries can be spontaneously broken by the VEVs of $U(1)_A$ charged matter fields X_i, producing axions with

$$f_a \sim \langle X_i \rangle \ll 10^{16} \text{ GeV}.$$

This can be examined within a low energy effective theory with softly broken global SUSY.

Tree level stabilization of open string saxion:

$$\text{PQ sector: } \{X_1, X_2\} \quad \left(X_i = s_i + ia_i + \sqrt{2}\theta\tilde{a}_i + \theta^2 F^{X_i}\right)$$

$$W_{\rm PQ} = \frac{\lambda}{M_{\rm Pl}} X_1^3 X_2 \quad \left(U(1)_{\rm A} : X_1 \to e^{i\alpha} X_1,\ X_2 \to e^{-3i\alpha} X_2\right)$$

$$\Rightarrow \quad V_{\rm PQ} \simeq \sum_i \left|\frac{\partial W_{\rm PQ}}{\partial X_i}\right|^2 + \left(\frac{\lambda m_{3/2}}{M_{\rm Pl}} X_1^3 X_2 + {\rm c.c}\right)$$

$$\Rightarrow \quad |X_1|^2 \simeq 3|X_2|^2 \simeq \frac{1}{3\sqrt{3}\lambda} m_{3/2} M_{\rm Pl}$$

$$m_{s_i} \sim m_{\tilde{a}_i} \sim m_{3/2}, \quad m_{a_H} \sim m_{3/2}, \quad m_{a_L} = 0 \ \left(\sim f_\pi m_\pi / f_a\right)$$

$$\Rightarrow \quad f_a \sim \sqrt{m_{3/2} M_{\rm Pl}} \sim 10^{11} \text{ GeV for TeV scale SUSY scenario}$$

Radiative stabilization of open string saxion:

PQ sector: $\{X, \Phi = 5, \Phi^c = \bar{5}\}$ $\quad \left(X = s + ia + \sqrt{2}\theta\tilde{a} + \theta^2 F^X\right)$

$$W_{\rm PQ} = \lambda X \Phi \Phi^c \quad \left(U(1)_{\rm A} : X \to e^{i\alpha} X,\ \Phi\Phi^c \to e^{-i\alpha}\Phi\Phi^c\right)$$

$$K_{\rm PQ} = X^\dagger X - \frac{(X^\dagger X)^2}{M_{V_A}^2} + ... \quad \left(M_{V_A} \sim 10^{16}\ {\rm GeV}\right)$$

$$\Rightarrow \quad V = -\frac{\lambda^2\left(16 g_3^2 + 6 g_2^2 + 2 g_1^2 - 35\lambda^2\right) m_{3/2}^2}{(16\pi^2)^2}|X|^2 + \frac{m_{3/2}^2}{2M_{V_A}^2}|X|^4$$

$$\Rightarrow \quad \langle X \rangle = \frac{\lambda M_{V_A}}{16\pi^2}\sqrt{16 g_3^2 + 6 g_2^2 + 2 g_1^2 - 35\lambda^2}$$

$$m_s \sim \frac{\lambda m_{3/2}}{16\pi^2}, \quad m_{\tilde{a}} \simeq \frac{\lambda^2 m_{3/2}}{(16\pi^2)^2}, \quad m_{a_L} = 0 \ \ (\sim f_\pi m_\pi / f_a)$$

$$\Rightarrow \quad f_a \sim \frac{\lambda M_{V_A}}{16\pi^2} \sim \lambda \times 10^{14}\ {\rm GeV} \ \text{ is independent of } m_{3/2}.$$

If these two type of open string axions exist together, and both of them couple to $G\tilde{G}$,

$$f_{a_{QCD}} \sim \text{Min}\left(\sqrt{m_{3/2}M_{\text{Pl}}},\ \lambda \times 10^{14}\ \text{GeV}\right)$$

$$f_{a_L} \sim \text{Max}\left(\sqrt{m_{3/2}M_{\text{Pl}}},\ \lambda \times 10^{14}\ \text{GeV}\right)$$

Both of these open string axion sectors involve SUSY-breaking auxiliary components of $\mathcal{O}(m_{3/2})$:

$$\frac{F^{X_1}}{X_1} = \frac{F^{X_2}}{X_2} = -\frac{2}{3}m_{3/2}, \qquad \frac{F^X}{X} = m_{3/2}$$

$$\Rightarrow \quad \text{Gauge mediated soft masses} \sim \frac{m_{3/2}}{8\pi^2}$$

Light axions and SUSY breaking in KKLT axiverse

1) Light axions:

* Ultralight axions with $f_{a_u} \sim 10^{16}$ GeV
* Ultralight axion with $f_{a_L} \sim \text{Max}\left(\sqrt{m_{3/2}M_{\rm Pl}},\ \lambda \times 10^{14}\ \text{GeV}\right)$
* QCD axion with $f_{a_{QCD}} \sim \text{Min}\left(\sqrt{m_{3/2}M_{\rm Pl}},\ \lambda \times 10^{14}\ \text{GeV}\right)$

2) SUSY breaking:

* Overall volume modulus mediation :

$$\frac{F^{T_m}}{T_m + T_m^*} = \frac{F^{T_u}}{T_u + T_u^*} = \frac{m_{3/2}}{\ln(M_{\rm Pl}/m_{3/2})}$$

* Anomaly mediation and gauge mediation of $\mathcal{O}(m_{3/2}/8\pi^2)$ comparable to the overall volume modulus mediation

Conclusions

* String theory may realize an axiverse scenario involving many light axions including the QCD axion.

* We propose a concrete scheme of moduli stabilization realizing an axiverse scenario, which stabilizes all moduli by flux, D-term, $W_{\rm NP}$ and a sequestered $V_{\rm lift}$, with a Kähler potential given at the leading order in g_s and α' expansions.

* This scheme can give a QCD axion with $f_{a_{QCD}} \sim 10^{11} - 10^{12}$ GeV, and ultralight axions with a wide range of different f_{a_L}, while avoiding the cosmological moduli problem.

* Soft SUSY breaking terms in this scheme receive comparable contributions from 1) overall volume modulus mediation, 2) anomaly mediation, 3) gauge mediation: Deflected mirage mediation