KKLT axiverse with intermediate scale axions

K. Choi, KSJ, K-I. Okumura and M. Yamaguchi, JHEP06(2011)049
K. Choi and KSJ, to appear soon

Kwang Sik JEONG

Tohoku University

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Outline

- Axion solution to the strong CP problem
- String axiverse
- Axiverse from KKLT with anomalous U(1) gauge symmetry
- Pattern of supersymmetry breaking
- Summary

Finally, the Higgs boson has been discovered, but so far with no direct hint for new physics beyond the SM. It looks just like the SM Higgs boson.

However, many reasons to consider new physics beyond the SM:

- Naturalness
  - Gauge hierarchy problem
  - Strong CP problem
- Unknown components such as dark energy and dark matter
- ...

These may indicate an extension of the SM with supersymmetry and Peccei-Quinn symmetry.

- Axion solution to the strong CP solution

Why is the CP violation in QCD tiny?

$\int dx^4 \frac{\theta}{8\pi^2} G\tilde{G}$: bound from the neutron EDM, $|\theta|<10^{-10}$

Axion solution

Peccei and Quinn (1977)

The idea is to replace θ by a dynamical field (axion) transforming non-linearly under $U(1)_{PQ}$.
PQ is explicitly broken by QCD instantons, and consequently the axion is stabilized at a CP conserving minimum.

Questions

Qunatum gravity generally breaks global symmetry.

Astrophysical and cosmological constraints require the PQ breaking scale to be $10^{9\text{-}12}$ GeV.

(upper bound unless the initial misalignment is very small, or there is a late time entropy production after QCD phase transition.)

- What is the origin of the global PQ symmetry of high quality?
- How can we achieve an intermediate PQ scale?

These may be addressed in string theory.

- String axiverse

String compactification involves many axions originating from higher-dim anti-symmetric tensor fields, and one of them may serve as the QCD axion.

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

Realization in KKLT

See also, Bobkov Braun, Kumar, Raby (2010); Acharya, Bobkov, Kumar (2010); Higaki, Kobayashi (2011); Cicoli, Goodsell, Ringwald (2012)

Kahler moduli $\{T_N\}=\{T_n, T_i\}$, where we define
T_n as the exponent of NP superpotential term: $W_{NP} = \sum_n A_n e^{-a_n T_n}$

Then moduli are fixed by SUSY conditions, $\partial_i K = \partial_n W + (\partial_n K) W = 0$

- T_n obtains a large SUSY mass ~ $\ln(M_{Pl}/m_{3/2}) m_{3/2}$.
- $\mathrm{Re}(T_i)$ gets mass ~ $m_{3/2}$ after adding a sequestered V_{lift}.

Conlon (2006); Choi and KSJ (2007)

Ultra-light axions

c.f. Blumenhagen, Moster, Plauschinn (2007)

$\mathrm{Im}(T_i)$ only obtains a tiny mass from higher order NP effects.

- Decay constant is typically around $M_{Pl}/8\pi^2 \sim M_{GUT}$.
- To avoid overclosure of the Universe, the initial misalignment should be less than 10^{-3} in thermal cosmology with $H_{inf} > m_{3/2}$, while $< 10^{-2}$ in non-thermal.
- Axion quantum fluctuations produced during inflation result in isocurvature CMB fluctuations.

  Axion DM can be compatible with low-scale inflation models with $H_{inf} < 10^{10}$ GeV.

  (but, mechanisms to suppress isocurvature fluctuation)

KSJ and Takahashi (2013); Folkerts, Germani, Redondo (2013)

Today's talk

We propose a concrete scheme of moduli stabilization for axiverse where some of axions have decay constant << M_{GUT}.

This is realized in models with anomalous U(1) gauge symmetry.

- Anomalous U(1) gauge symmetry

We consider generic string compactification with many Kahler moduli, where some of them transform non-linearly under $U(1)_A$ to implement the Green-Schwarz anomaly cancellation:

GS modulus: $T_\alpha \to T_\alpha + \delta_{\rm GS}\Lambda(x)$ with $\delta_{\rm GS} \sim 1/8\pi^2$

matter field: $X \to e^{iq\Lambda(x)} X$ (added to cancel a moduli-induced FI D-term)

The $U(1)_A$ gauge boson is generally heavier than M_{GUT} because its mass receives the Stuckelberg contribution:

$$M_A \geq M_{\rm ST} \text{ where } M_{\rm ST}^2 = \delta_{\rm GS}^2 \frac{\partial^2 K}{\partial T_\alpha^2} M_{Pl}^2 \approx \left(\frac{M_{Pl}}{8\pi^2}\right)^2$$

D-flat direction of anomalous U(1)

Low energy consequences of anomalous U(1) strongly depend on which of T_α and X is the main component of the D-flat direction:

$$R \equiv \frac{(\text{Stuckelberg mass})^2}{(\text{Fayet-Iillopolous term})} = \frac{\delta_{\rm GS}}{2}\frac{\partial_\alpha^2 K}{\partial_\alpha K}$$

- For R>>1, the D-flat direction is mostly the matter field X, while the GS modulus T_α is absorbed into the gauge boson.
  $\rightarrow$ moduli stabilization by the D-flat condition
- For R<<1, the D-flat direction is mostly T_α. This is the case when the moduli-induced FI term vanishes in SUSY limit.

c.f. Anderson, Gray, Lukas (2009)

- KKLT axiverse with anomalous U(1)'s

Low energy effective theory below M_{GUT} includes two sectors:

- Kahler moduli $\{T_N\}$ of two classes as in the original case

  $\{T_n\}$=(exponent of a NP superpotential term)
  $\{T_i\}$=(invariant of superpotential)

  Some of them are from the D-flat direction of anomalous U(1) with $R \ll 1$, and with/without W_{NP}.

- PQ sector with matter field X, which is charged under global U(1) (=the global part of anomalous U(1) gauge symmetry)

  This sector is from the D-flat direction with $R \gg 1$.

$f_a \sim M_{GUT}$ for closed-string axion, and $f_a \ll M_{GUT}$ for open-string axion

- Moduli stabilization and SUSY breaking

The Kahler potential for $\{T_N\}$ is no-scale at the leading order in α' and string loop expansion:

$$K_0 = -2\ln V_{\rm CY}$$

where V_{CY} is a homogeneous function of degree 3/2.

✓ mass spectrum:
$$\begin{cases} m_{{\rm Re}(T_n)} \simeq m_{{\rm Im}(T_n)} \simeq m_{\tilde{T}_n} \simeq 2\ln(M_{Pl}/m_{3/2})\times m_{3/2}, \\ m_{{\rm Re}(T_i)} \simeq \sqrt{2} m_{3/2},\ m_{{\rm Im}(T_n)} \simeq 0,\ m_{\tilde{T}_i} \simeq m_{3/2} \end{cases}$$

✓ universal moduli F-term, independently of the detailed form of K

Choi and KSJ (2006)

$$\frac{F^n}{T_n + T_n^*} \simeq \frac{F^i}{T_i + T_i^*} \simeq \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})}$$

✓ mixed anomaly-moduli mediation: m_{soft}~1TeV for $m_{3/2}$~40 TeV

Choi, Nilles, Fallowski, Olechowski (2005)

- Saxion stabilization and SUSY breaking

1. Interplay between higher dim superpotential and SUSY breaking

two PQ matter fields with $W = \frac{\lambda}{M_{Pl}} X_1^3 X_2$

X_1 and X_2 are stabilized at $|X_1|^2=3|X_2|^2 \sim m_{3/2}M_{Pl}$.

✓ axion decay constant is around 10^{11} GeV.

✓ the fermions and scalar bosons except the axion have mass$\sim m_{3/2}$.

✓ universal F-term:

$$\frac{F^{X_1}}{X_1} = \frac{F^{X_2}}{X_2} \simeq -\frac{2}{3} m_{3/2}$$

✓ gauge mediation from the loops of PQ fields ($W=X_1\Phi\Phi^c$): it is as important as anomaly mediation.

2. Radiative stabilization

$-3e^{-K/3} = |X|^2 - \frac{1}{M_A^2}|X|^4$ after integrating out the heavy $U(1)_A$ gauge boson.

$W = yX\Phi\bar{\Phi}$ where $\Phi + \bar{\Phi}$ are 5+$\bar{5}$ of SU(5).

✓ the VEV of X is fixed by $M_A \sim M_{GUT}$ and y (independent of $m_{3/2}$):

$$|X| \approx \frac{y}{8\pi^2}\sqrt{g^2 - y^2}M_A \approx y \times 10^{14}\,\mathrm{GeV}$$

✓ the radial scalar has mass~ $y m_{3/2}/(8\pi^2)$.

✓ the axino is the LSP with a small mass~ $y^2 m_{3/2}/(8\pi^2)^2$.

✓the F-term: $\frac{F^X}{X} \simeq m_{3/2}$

- Pattern of soft terms

Soft terms receive comparable contributions from anomaly, moduli, and gauge mediation. Everett, Kim, Ouyang, Zurek (2008);Choi, KJS, Nakamura, Okumura, Yamaguchi (2009)

→ Deflected mirage mediation

- Gaugino masses have a universal value at an intermediate scale as in the mirage mediation, but sfermions do not show such pattern.
- Thermal inflation can be driven by the saxion potential. Then one can avoid moduli-induced gravitino problem, and there are no isocurvature fluctuations associated with the QCD axion.

Let me summarize.

- String theory provides a natural framework to realize the axion solution to the strong CP problem.

- KKLT moduli stabilization with anomaly U(1) gauge symmetry realizes axiverse where axions have a decay constant in a wide range from M_{GUT} to an intermediate scale.

- In such axiverse scenario,

  - anomaly, moduli and gauge mediation are all important, leading to deflected mirage mediation.

  - saxion-driven thermal inflation can change cosmological aspects.

thank you!!