Axion Monodromy Quintessence

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Motivation

- Time varying dark energy
- Evading unwanted corrections (e.g. KK couplings)
  $\rightarrow$ shift symmetry $\rightarrow$ axion
- A comprehensive survey for axion quintessence in IIB string theory
- Several corrections from warping and non-perturbative effect
- A contribution to the CMB polarization angle

General Idea

Setup : General ideas

4D Axions

Shift symmetry

broken by non-perturbative effect, or boundaries

Generating potentials

$$V(\phi) \sim M_P^4 e^{-S_{\text{inst}}} \cos\frac{\phi}{f_a}$$

by instanton effect

$$V(\phi) \sim \mu^4 \frac{\phi}{f_a}$$

will be explain later

ϕ : canonically normalized axion, f_a : axion decay constant

Non-perturbative potential

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \quad \text{with} \quad V(\phi) \sim M_P^4 e^{-S_{\text{inst}}} \cos\frac{\phi}{f_a}$$

Quintessence condition ⟹ Overdamping with Hubble friction

[06 Svrcek]

$$f_a \lesssim \frac{M_P}{S_{\text{inst}}}, \quad H^2 \geq \frac{M_P^4 e^{-S_{\text{inst}}}}{f_a^2}$$

needs to include "N" axions

$$S_{\text{inst}} \sim 280, \quad N \sim 10^5$$

Huge number of axion is needed.

⟹ Consider the potential from boundaries!

Boundary potential

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \quad \text{with} \quad V(\phi) \sim \mu^4 \frac{\phi}{f_a}$$ *linear potential*

Requiring slowly varying potential: $M_P^2 \frac{V''}{V} \lesssim 1, \quad M_P^2 \left(\frac{V'}{V}\right)^2 \lesssim 1$

→ $\phi \gtrsim M_P$

Pressure density ratio around $\phi \sim \phi_0$

$$w_\phi = \frac{p_\phi}{\rho_\phi} \sim \frac{M_P^2 - 6\phi_0^2}{M_P^2 + 6\phi_0^2} - \frac{24M_P^4}{(M_P^2 + 6\phi_0)^2} \frac{z}{1+z} + \cdots$$

Recent observational bound [10 Komatsu et.al. and others]

$$w_{\rm DE}(z) = w_0 + w_1 \frac{z}{1+z}, \quad w_0 = -0.93 \pm 0.13, \; w_1 = -0.41^{+0.72}_{-0.71}$$

→ $\phi \geq 1.29 M_P$

Details of setup

IIB string setup

[06 Svrcek-Witten]

$$C_2 = \alpha' a^a w_a, \quad \int_{\Sigma_a^{(2)}} w_b = \delta_{ab} \quad \Rightarrow \quad a \sim a + (2\pi)^2$$

Kinetic term

$$S_{\rm IIB} = \frac{1}{(2\pi)^7 g_s^2 \alpha'^4} \int \left[R \wedge *1 - \frac{g_s^2}{2} F_3 \wedge *F_3 + \cdots \right]$$
$$= \int d^4x \sqrt{-g_4} \left[\frac{M_P^2}{2} R^{(4)} - \frac{f_a^2}{2} (\partial a)^2 + \cdots \right]$$

with $M_P^2 \sim L^6 M_s^2, \quad f_a^2 \sim \frac{M_P^2}{L^4}$ where $V_{CY} = L^6 \alpha'^3$

$\Rightarrow$ slow-roll condition becomes $a \gtrsim L^2/g_s$

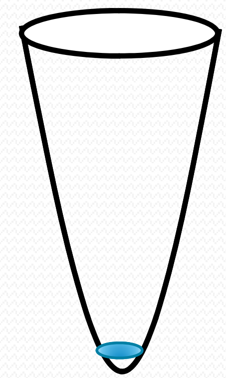
Constraint from red giant (low-energy physics)

$$f_a > 10^9 \text{ GeV} \quad \Rightarrow \quad M_s \gtrsim 10^4 \text{ GeV}, \quad L \lesssim 10^5$$

Potentials from brane

[08 Silverstein-McAllister-Westphal]

NS5-brane at the bottom of a warped throat



$$S_{\rm NS5} = -\frac{1}{(2\pi)^5 g_s^2 \alpha'^3}\int d^6x\sqrt{-\det(P[g+g_sC])}$$

$$ds^2 = e^{2A}dx_4^2 + e^{-2A}dy_6^2$$

$$V_0 = \frac{e^{4A_m}}{(2\pi)^5 g_s^2\alpha'^2}\sqrt{\ell^4 + g_s^2 a^2} \quad \sim \frac{e^{4A_m}M_s^4}{g_s}a \qquad \left(a \ll \frac{\ell^2}{g_s} \ll \frac{L^2}{g_s}\right)$$

For instance, $L \sim 10,\ g_s \sim 1,\ a \sim L^2$

$$e^{A_m} \sim 10^{-28}$$

$$e^{A_m} \sim \exp\left(-\frac{2\pi N}{3g_s M^2}\right)$$

can be stably realized
as like Giddings-Kachru-Polchinski (tip of the warped deformed conifold)

Back reaction and corrections

Back reaction of NS5-brane

Five form and warp factor are closely related.

$$F_5 = dC_4 + C_2 \wedge H_3$$

(or compactified NS5 → effective D3)

$$\rightarrow \quad \delta e^{-4A} \sim \frac{g_s \alpha'^2 a}{\pi r^4}$$

Volume change due to warping

e.g. Kahler correction [08 Douglas-Frey-Underwood-Torroba]

$$\frac{K}{M_P^2} = -3 \ln \left[T + \bar{T} + \frac{2\tilde{V}_w}{\tilde{V}_{CY}} \right] \quad \left(\tilde{V}_w = \int d^6 y \sqrt{\tilde{g}_6} e^{-4A}, \;\; \tilde{V}_{CY} = \int d^6 y \sqrt{\tilde{g}_6} \right)$$

$$\delta \left(\frac{\tilde{V}_w}{\tilde{V}_{CY}} \right) \sim \frac{g_s \alpha'^2}{\pi r^4_{\text{cutoff}}} a \qquad T \sim L^4$$

Moduli stabilization and axion

$$V_{\rm mod} = e^{\frac{K}{M_P^2}}\left(K^{I\bar J}D_I W D_{\bar J}\bar W - \frac{3}{M_P^2}|W|^2\right) + V_{\rm loc}$$

SUSY min: $D_I W = 0$

$\sim m_{3/2}^2 M_P^2$ $\qquad m_{3/2} \sim e^{\frac{K}{2M_P^2}}\frac{<W>}{M_P^2}$

Together with warping correction in Kahler

$$\delta V \sim V_{\rm mod}\frac{a}{L^4}$$

taking $g_s \sim 1,\ r_{\rm cutoff} \sim \sqrt{\alpha'},\ a \sim L^2$

e.g. $V_{\rm mod} \sim \left(\frac{M_{SB}^2}{M_P}\right)^2 M_P^2 = M_{SB}^4 \sim (10\,{\rm TeV})^4$

$\delta V \sim \frac{M_{SB}^4}{L^2} \lesssim \Lambda^4$ ⇒ $L \gtrsim 10^{31}$ too large…

Even Low energy SUSY breaking

$M_{\rm compact} \sim \frac{1}{L\sqrt{\alpha'}} \sim 10^{-96}\,{\rm eV}$

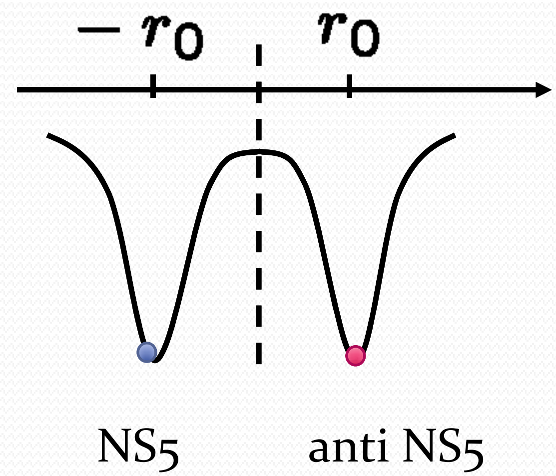
Leading cancellation

$\mathbb{Z}_2$ position symmetric setup: $r \to -r$

$\overline{\text{NS5}}$ → $-1\ \text{NS5} + \text{NS5}\text{–}\overline{\text{NS5}}$

→ $-a\ \text{D3} + a\ \text{D3}\text{–}\overline{\text{D3}}$

r dependence: *leading* *sub-leading*



Leading suppression

$$V_w = \int d^6y\sqrt{\tilde{g}_6}e^{-4A}$$
$$\sim \left(\frac{N}{2}+a\alpha'^2\right)\int dr\frac{|r+r_0|^5}{|r+r_0|^4} + \left(\frac{N}{2}-a\alpha'^2\right)\int dr\frac{|r-r_0|^5}{|r-r_0|^4}$$
$$\sim N(L^2+\cdots)$$

leading

$\left(\frac{N}{2}+a\alpha'^2\right)\text{D3}$ $\left(\frac{N}{2}-a\alpha'^2\right)\text{D3}$

+

sub-leading

$a\ \text{D3}\text{–}\overline{\text{D3}}$ pairs

No axion contributions to leading order $e^{-4A} \sim \mathcal{O}(\frac{1}{r^4})$

As like tadpole cancellation in CY compactification

Brane-anti brane in warped throat

3 Brane-anti 3 brane force $\sim \mathcal{O}\left(\frac{1}{r^4}\right)$

D3-brane warped throat: $e^{-4A} \sim \mathcal{O}\left(\frac{1}{r^4}\right)$

Brane-anti brane backreaction in warped throat [08 DeWolfe-Kachru-Murllgan]

$\delta e^{-4A} \sim \frac{a\alpha'^2}{r^8} r_*^4$,non-constant dilaton, and non-ISD

IR scale of the throat: $\frac{r_*}{\sqrt{\alpha'}} \sim e^{A_m}$

Contribution from dangerous IR

$$\delta V_w \sim \int_{r_*} dr r^5 \frac{a\alpha'^2}{r^8} r_*^4 \sim a\alpha'^2 r_*^2$$

$$\delta\left(\frac{V_w}{V_{CY}}\right) \sim a\frac{r_*^2}{\alpha'} \sim ae^{2A_m}$$

Same result from exact IR sol.

[09 McGuirk-Shiu-Sumitomo]
[09 Bena-Grana-Halmagyi]

Brane-anti brane correction in Kahler

Combining brane-anti brane and volume change due to warping

$$V_1 \sim V_{\rm mod}\frac{a}{L^4}e^{2A_m} \sim \frac{M_{SB}^4}{L^2}e^{2A_m}$$

(even true for superpotential correction)

The corrected potential dominates.

$$V_1 \sim \Lambda^4 \quad \Longrightarrow \quad e^{A_m} \sim \frac{\Lambda^2}{M_{SB}}L \sim 10^{-32}L \quad \text{where} \quad a \sim L^2$$

Compare with DBI potential

$$\Longrightarrow \quad V_0 \sim M_s^4 e^{4A_m}L^2 \sim \frac{\Lambda^4}{L^6}\boxed{\frac{\Lambda^4 M_P^4}{M_{SB}^8}} \lesssim \Lambda^4 \qquad \text{If } M_{SB} \gtrsim 1\ \text{TeV}$$

(Moduli problem will be discussed later)

Quintessence should be realized with the potential from brane-anti brane.

Note: Brane-anti brane effect in DBI

$$\delta V \sim M_s^4 \delta e^{4A_m}a \sim M_s^4 e^{8A_m}\frac{a^2\alpha'^2}{r^4_{\rm distance}}$$

Non-perturbative corrections

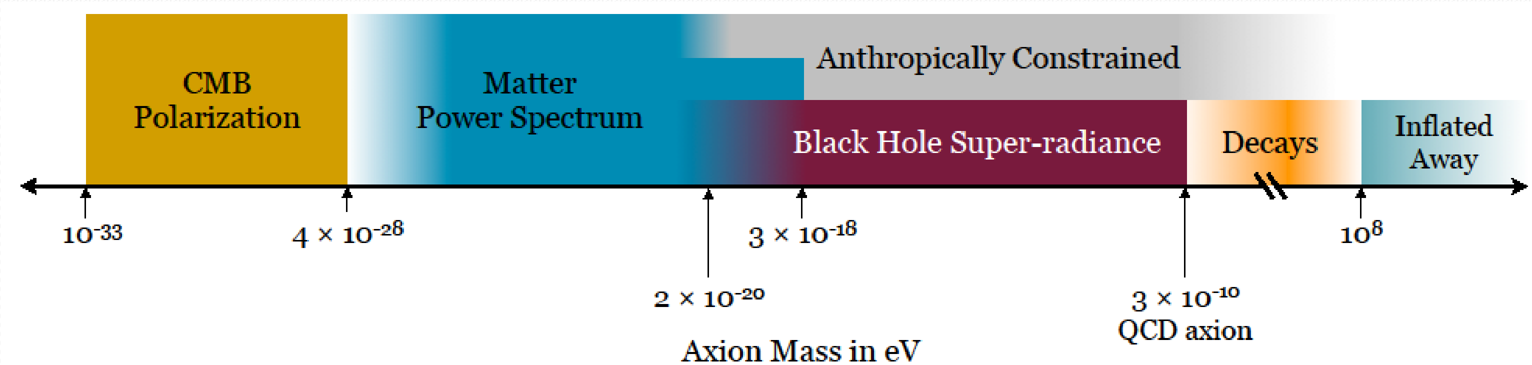
avoided if $L \gtrsim \mathcal{O}(10)$

Rotation Angle of CMB Polarization

Rotation of the CMB polarization

String Axiverse map

[09 Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell]



Our effective mass scale

$$m_\phi \lesssim \sqrt{\frac{\mu^4}{f_a \phi}} \sim \frac{\Lambda^2}{M_P} \sim 10^{-33}\,\mathrm{eV}$$

⇒ CMB Polarization

Topological coupling

C_2 ⇒ D5-brane wrapping 2-cycle

$$S_{D5} = -T_{D5}(2\pi\alpha')^2 \int d^6x \sqrt{-\tilde{g}_6} e^{-\phi} \frac{1}{4} F_{\mu\nu}^2 + T_{D5}(2\pi\alpha')^2 \int \frac{1}{2} C_2 \wedge F \wedge F$$

Estimation of angle

$$\frac{\mathcal{L}}{\sqrt{-g_4}} = \frac{1}{2}(\partial\phi)^2 + \frac{\mu^4}{f_a}\phi - \frac{1}{4g^2}\phi + \frac{\phi}{8g^2L^2f_a}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

Free wave: $\vec{D} = \vec{E} + \frac{\phi}{L^2 f_a}\vec{B}, \ \vec{H} = \vec{B} - \frac{\phi}{L^2 f_a}\vec{E}$

Rotation angle (difference)

$$\Delta\alpha = \frac{1}{L^2 f_a}\int_{\text{recombination}}^{\text{present}} dt\dot{\phi}$$

$$\dot{\phi} \sim -\sqrt{\frac{10^{-123}}{3}\frac{M_P}{\phi}}$$

$$\Delta\alpha \lesssim \frac{M_P^2}{\phi_0} \times 10^{-62} \times 10^{33} \ll 10^{-1}$$

Current bound [10 Komatsu et.al.]

$$-6.6 \times 10^{-2} \leq \Delta\alpha \leq 7.0 \times 10^{-3}$$ satisfied if $\phi_0 \sim 100 M_P$

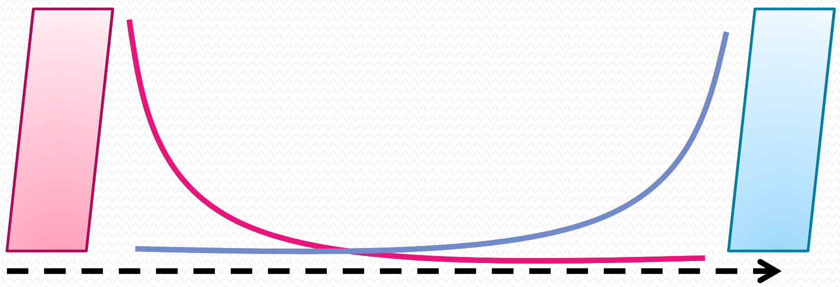
without violating any other bounds

Discussions

Comments

Light particles

Large warping required in our model ⇨ many light particles



- As like in RS II, KK-couplings are well suppressed on the brane.
- KK exchange is highly suppressed.

Constant term

There may be so many constants terms after the compactification.

$$V_{\text{total}} = \mu^4 a + C$$

It is easy to absorb into linear term, if C is not significantly large.

Remaining Issues

- SUSY breaking via anomaly mediation
  $\rightarrow$ C2 axion behaves like gauge coupling
- Cosmological moduli problem
  $\rightarrow$ requires additional physics (thermal inflation etc.)
- (Connection to) Inflation?
- Standard Model sector? QCD axion and hierarchy?
- …

Thank you!