Axion Monodromy Quintessence

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Motivation

- Time varying dark energy
- A comprehensive survey of axion quintessence in IIB string theory
- Several corrections from warping and non-perturbative
- A contribution to the CMB polarization angle
- SUSY breaking (via anomaly mediation)

General Idea

Setup : General ideas

4D Axions

Shift symmetry

broken by non-perturbative effect, or boundaries

Generating potentials

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

by instanton effect

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

We will 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

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

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

$$\Longrightarrow \quad \phi \gtrsim M_P$$

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

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

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

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

$$\Longrightarrow \quad \phi \geq 1.29 M_P$$

Comments on linear potential

Small cosmological constant

In string setup, D-branes (boundaries of strings) can sit on highly warped throat.

$$\mu^4 \frac{\phi}{f_a} \sim \Lambda^4 \sim 10^{-123} M_P^4$$

due to warping suppression

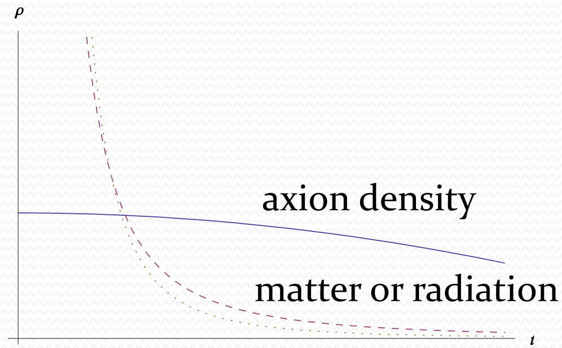
(We will see more detail later.)

Coincidence problem? $\rho_m \sim \rho_{DE}$ at present

$$\Gamma \equiv \frac{V''V}{(V')^2} > 1, \quad \left|\frac{\Gamma'}{\Gamma(V'/V)}\right| \ll 1 \quad \text{but} \quad \left|\frac{\Gamma'}{\Gamma(V'/V)}\right| = 2(1+\Gamma) \quad \ldots$$

Linear potential is sensitive to initial conditions.

→ Fine-tuning of end of universe may help.



Detail 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 $V_{CY} = L^6 \alpha'^3$

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

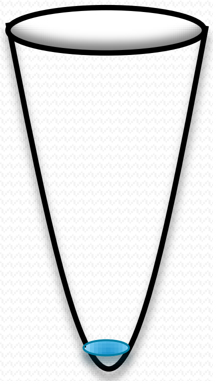
Constraint from red giant (low-energy physics)

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

Potentials from brane

[08 Silverstein-McAllister-Westphal]

NS5-brane at the bottom of a warped throat



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

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

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

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

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

can be stably realized

as like Giddings-Kachru-Polchinski (tip of the warped deformed conifold)

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

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)

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

Warping correction in Kahler

[08 Douglas-Frey-Underwood-Torroba]

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

$$\delta \left(\frac{V_w}{V_{CY}} \right) \sim \frac{g_s \alpha'^2}{\pi r_{\text{cutoff}}^4} a$$

$T \sim L^4$ → will be explained later... (if necessary)

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

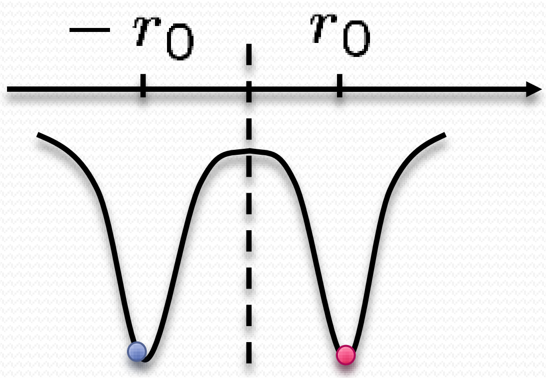
Even Low energy SUSY breaking

$\delta V \sim \frac{F^2}{L^2} \lesssim \Lambda^4$ → $L \gtrsim 10^{31}$ too large... $\qquad M_{\rm compact} \sim \frac{1}{L\sqrt{\alpha'}} \sim 10^{-96}\,{\rm eV}$

(neglecting moduli problem for a moment...)

Leading cancellation

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



NS5 anti NS5

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

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

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

$\left(\frac{N}{2} + a\alpha'^2\right)$D3 $\left(\frac{N}{2} - a\alpha'^2\right)$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: $\frac{r_*}{\sqrt{\alpha'}} \sim e^{A_m} \sim \frac{2\pi N}{3 g_s M^2}$

Contribution from dangerous IR

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

$$\frac{\delta V_w}{V_{CY}} \sim a \frac{r_*^2}{\alpha'} \sim a e^{2A_m} \quad \text{with} \quad r_{\text{cutoff}} \sim \sqrt{\alpha'}$$

Same result can be obtained from the IR analyses.

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

Brane-anti brane correction in Kahler

Combining brane-anti brane and warping correction in Kahler

$$V_1 \sim V_{\text{mod}} \frac{a}{L^4} e^{2A_m} \sim \frac{F^2}{L^2} e^{2A_m}$$

This potential can be the dominant potential.

$$V_1 \sim \Lambda^4 \quad \Rightarrow \quad e^{2A_m} \sim \frac{\Lambda^4}{F^2} L^2 \sim 10^{-63} L^2$$

If $F^{1/2} \gtrsim 1\,\text{TeV}$

Compare with DBI potential

$$\Rightarrow \quad V_0 \sim M_s^4 e^{4A_m} L^2 \sim \frac{\Lambda^4}{L^6} \boxed{\frac{\Lambda^4 M_P^4}{F^2}} \lesssim \Lambda^4$$

(Moduli problem will be discussed later)

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

Note: brane-anti brane effect in DBI

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

harmless

Other corrections

Instanton corrections

Holomorphically allowed **superpotential**

$$\delta W = Ae^{-cT} + Be^{-cT-c(a-\tau b)/(2\pi)^2}$$

Euclidean D3 Euclidean D1 correction to Euclidean D3

→ can destabilize the moduli…

→ We should use the superpotential from D7 gaugino condensation.

[08 Silverstein-McAllister-Westphal]

Kahler potential

$$\frac{K}{M_P^2} = -3\ln\left[T + \bar{T} + C\,\mathrm{Re}\, e^{-2\pi v_+ -(a-\tau b)/(2\pi)^2} + \cdots\right]$$

→ $\delta V \sim V_{\mathrm{mod}} C \frac{a}{L^4} e^{-2\pi L^2} \lesssim \Lambda^4$ → $L \gtrsim \mathcal{O}(10)$

$(v_+ \sim L^2)$

Comments on B2 axion

$B_2 = \alpha' b^a w_a$ can also be axions.

N=1 Calabi-Yau orientifolds with O3/O7-planes

$$\frac{K}{M_P^2} \sim -3 \ln \left[T + \bar{T} + \frac{3}{2 g_s} c^{ij} b_i b_j \right]$$

In general, we have large potential mass term as like η problem.

$$\delta V \sim V_{\rm mod} b^2$$

Since there are no C2 axion dependence in Kahler except for warping corrections, we can use it for string cosmology.

As like, *axion monodromy inflation.* [08 Silverstein-McAllister-Westphal]

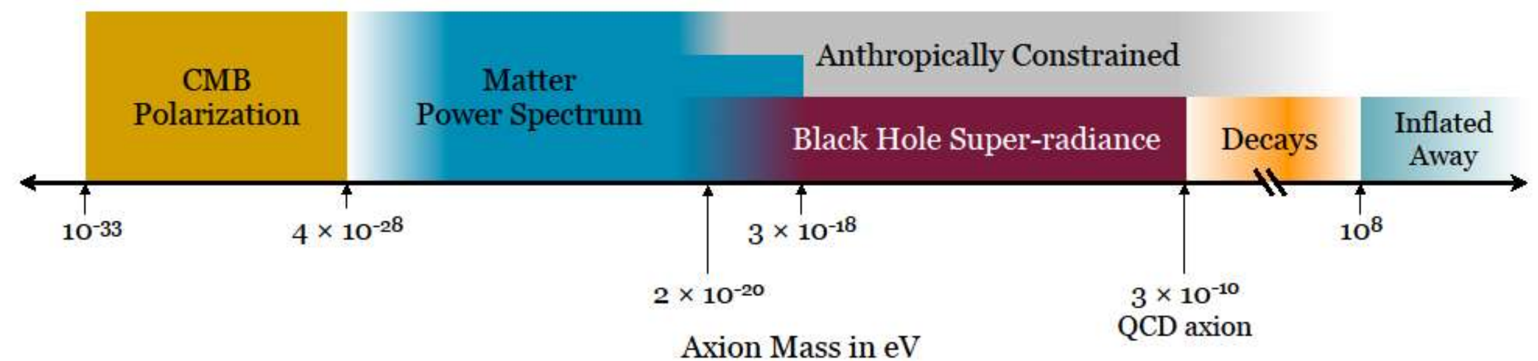
[09 Flauger-McAllister-Pajer-Westphal-Xu]

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

SUSY Breaking & Anomaly Mediation

SUSY breaking and mediation

Suppression of direct coupling [07 Kachru-McAllister-Sundrum]

$$c\int d^2\theta d^2\bar{\theta}\hat{\mathcal{O}}Q^\dagger Q$$

$\hat{\mathcal{O}}$: hidden sector non-chiral operator

Q : visible chiral superfield

For instance,

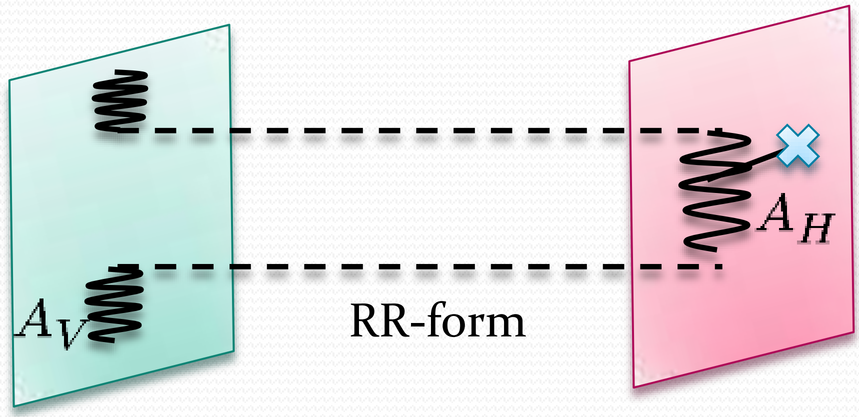
SU(2) x SU(2) invariant non-chiral supermultiplet in Klebanov-Witten (Klevnov-Strassler) theory

➡ $\mathcal{O}_8 = W_\alpha^2 W_{\dot{\alpha}}^2$ highest component has dimension $\Delta = 8$

➡ $c \propto \frac{\Lambda_{\mathrm{IR}}^4}{\Lambda_{\mathrm{UV}}^4} = e^{4A_m}$ ➡ Easily suppressed!

Higher form mediation

[07 Verlinde-Wang-Wijnholt-Yavin]



Our axion brane SUSY breaking branes

$$C_4 = \mathcal{C}_a w^a + \cdots$$

$$\mathcal{L}_{\rm CS} = C_4 \wedge \mathcal{F}_{V,H}$$

$$\Rightarrow \quad \mathcal{L}_{\mathcal{C}} = \mathcal{C} \wedge d(\mathcal{A}_V + \mathcal{A}_H) + \frac{1}{2m_A^2}|d\mathcal{C}|^2$$

dualizing $\mathcal{C}$

$$\Rightarrow \quad \mathcal{L}_\phi = \frac{1}{2} m_A^2 |d\phi + \mathcal{A}_V + \mathcal{A}_H|^2 \quad \Rightarrow$$

massless combination

$U(1) \quad \mathcal{A}_V - \mathcal{A}_H$

Hypercharged anomaly mediation

[07 Dermisek-Verlinde-Wang]

Gauge kinetic term

$$\frac{1}{4}\int d^2\theta f_h(\psi_m) W^\alpha W_\alpha + c.c.$$

SUSY breaking source: $F^m = e^{K/2M_P^2} K^{mn} D_n W$

Gaugino mass: $\tilde{M}_1 = F^m \partial_m \ln[\mathrm{Re}\, f_h]$

Anomaly mediation

Scalar mass: $\delta m_i^2 = -\frac{3}{10\pi^2} g_1^2 Y_i^2 M_1^2 \ln\left[\frac{m_A}{M_*}\right]$

However...

$$\frac{a}{(2\pi)^3 g_s}\frac{1}{4}F_{\mu\nu}^2 \;\Rightarrow\; a \sim -\frac{b_0}{16\pi^2}\ln\left[\frac{m_A^2}{M_*^2}\right]$$

negligible!

Bulk anomaly mediation

Anomaly mediation is like scale changing with SUSY breaking

$$\frac{1}{4}\int d^2\theta \left(\frac{1}{g^2} - \frac{b_0}{16\pi^2}\ln\left[\frac{m_A^2}{M_*^2}\right]\right) W_\alpha W^\alpha + c.c.$$

with $\quad m_A \to m_A e^{\theta^2 F/M_P}$

➡ Dilaton change $\quad \frac{1}{g_s} \to \frac{1}{g_s} - \frac{b_0}{4}\ln\left[\frac{m_A e^{\theta^2 F/M_P}}{M_*}\right]$

Supersymmetrize constant DBI term with spurion field

$$\int d^4x\sqrt{-g_4}\int d^2\theta d^2\bar{\theta} e^{4A_m}\frac{a}{(2\pi)^5 g_s \alpha'^2}\theta^2\bar{\theta}^2$$

[05 Choi-Falkowski-Niles-Olechowski]

GKP: $\quad e^{A_m} \sim e^{-\frac{2piM}{3g_sN}}$

doesn't cause serious contributions

Discussions and Outlook

Moduli Stabilization and moduli problem

$V_{\rm mod} \sim m_{3/2} M_P^2 \sim M_{SB}^4$ → too small for reheating

→
- Using high scale moduli stabilization and quite small warping

  No danger in KK modes (work in progress) $m_{\rm mod} \gtrsim 100$ TeV
- Suitable scenario for earlier universe i.e. thermal inflation [95 Lyth-Stewart]
- Extra symmetry between UV and IR fixing moduli potential

etc… [95 Dine-Randall-Thomas]

New moduli problem

[06 Endo-Hamaguchi-Takahashi, Nakamura-Yamaguchi]

Gravitino overproduction even for $100\ \text{TeV} \lesssim m_{\rm mod} \lesssim 10^4\ \text{TeV}$

Still require the detail of high energy physics (SUSY breaking models, Inflation)

→
- Helicity suppression due to some of supersymmetric models
- R-parity odd particles [06 Dine-Kitano-Morisse-Shirman]
- Thermal inflation [09 Choi-Jeong-Park-Shin]

etc…