Axion Quintessence in String Theory

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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 effect
- SUSY breaking
- A contribution to the CMB polarization angle

Contents

- General idea
- Detailed setup
- Rotation angle of CMB angle
- Discussions
- Comments on SUSY breaking & anomaly mediation

General Idea

Setup : General ideas

4D Axions

Shift symmetry : good for suppressing several awkward couplings

→ 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]

$$f_a \lesssim \frac{M_P}{S_{\text{inst}}}, \quad H^2 \geq \frac{M_P^4 e^{-S_{\text{inst}}}}{f_a^2} \Rightarrow M_P^4 e^{-S_{\text{inst}}} \leq \frac{\Lambda^4}{S_{\text{inst}}^2} \quad \left(H^2 = \frac{\Lambda^4}{3M_P^2}\right)$$

needs to include "N" axions

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

Huge number of axions 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: $M_P^2 \frac{V''}{V} \lesssim 1, \quad M_P^2 \left(\frac{V'}{V}\right)^2 \lesssim 1$

$$\Rightarrow \quad \phi \gtrsim M_P$$

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]

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

$$\Rightarrow \quad \phi \geq 2.14 M_P$$

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.)

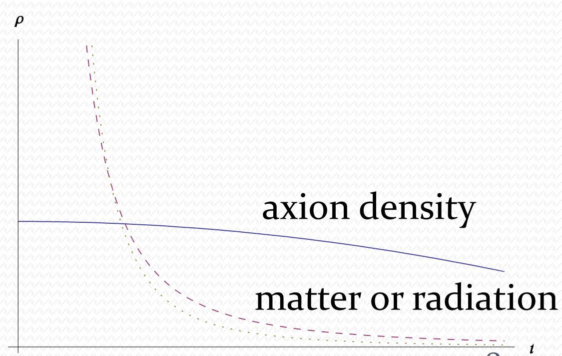
Coincidence problem?

$\rho_m \sim \rho_{\rm DE}$ 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.



Detailed 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

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

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 $a \gtrsim L^2/g_s$

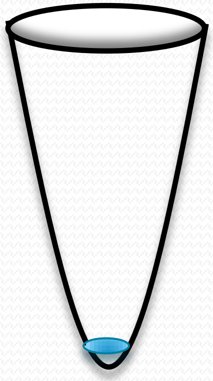
Constraint from red giant (low-energy physics)

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

Potentials from brane

[08 Silverstein-McAllister-Westphal]

NS5-brane at the bottom of a warped throat



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

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

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

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

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

e.g. [01 Giddings-Kachru-Polchinski]

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

can be stably-positioned
at the tip of the smoothed geometry (like 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. $V_{\rm mod} \sim \left(\frac{F}{M_P}\right)^2 M_P^2 = F^2 \sim (10\,{\rm TeV})^4$

Even Low energy SUSY breaking

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

too large…

(neglecting moduli problem for a moment…)

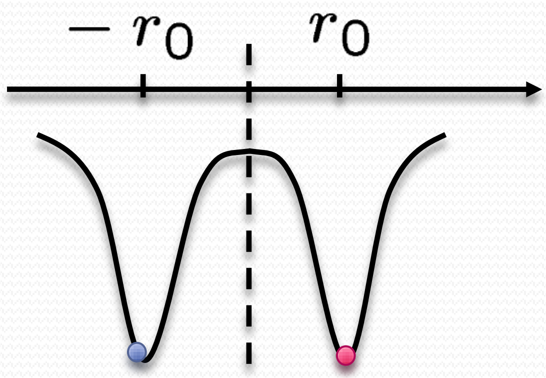
Leading cancellation

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

$\overline{\mathrm{NS5}}$ → $-1\ \mathrm{NS5} + \mathrm{NS5}-\overline{\mathrm{NS5}}$

→ $-a\ \mathrm{D3} + a\ \mathrm{D3}-\overline{\mathrm{D3}}$

r dependence: *leading* *sub-leading*



NS5 anti NS5

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

$a\ \mathrm{D3}-\overline{\mathrm{D3}}$ 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

$$\delta V_w \sim \int_{r_*} dr r^5 \frac{a\alpha'^2}{r^8} r_*^4 \sim a\alpha'^2 r_*^2 \sim a e^{2A_m} \alpha'^3$$

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

Brane-anti brane in warped throat

Same result from exact IR

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

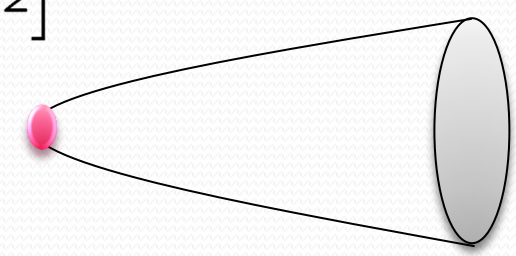
IR D3-anti D3 solution at the tip of deformed conifold

$$ds_{10}^2 = e^{2A} dx_4^2 + e^{-2A} d\tilde{s}_6^2$$

$$d\tilde{s}_6 \sim r_*^2 2^{2/3} 3^{1/3} \left[\frac{1}{2} d\tau^2 + d\Omega_3^2 + \tau^2 d\Omega_2^2 \right]$$

$$r^3 = r_*^3 \cosh \tau$$

$$\delta e^{-4A} \sim r_*^{-4} \frac{a\alpha'^2}{\tau}$$



Volume change

$$\delta V_w \sim \int_{\tau_{\rm IR}}^{\tau_{\rm UV}} d\tau \sqrt{\tilde{g}_6} \delta e^{-4A} \sim r_*^2 a\alpha'^2 (\tau_{\rm UV}^2 - \tau_{\rm IR}^2) \sim e^{2A_m} a\alpha'^3$$

where cutoff scales $\tau_{\rm UV}^2 - \tau_{IR}^2 \sim \mathcal{O}(1)$ ⇒ same as before

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 corrections)

The corrected potential dominates.

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

where $a \sim L^2$

Compare with DBI potential

$$\Rightarrow \quad V_0 \sim M_s^4 e^{4A_m} L^2 \sim \frac{\Lambda^4}{L^6}\boxed{\frac{\Lambda^4 M_P^4}{M_{SB}^8}} \lesssim \Lambda^4$$

If $M_{SB} \gtrsim 1\,\text{TeV}$

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

Note: Brane-anti brane effect in DBI

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

Non-perturbative corrections

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

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 [04 Grimm-Louis]

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

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

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

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]

Comments on C4 axion

$C_4 = c_4 \omega_4$ → Kahler multiplet $T = \sigma + i c_4$

Axion coupling → On D7-branes: $T_7 \int C_4 \wedge F \wedge F$

→ Embedded with preserving SUSY

→ Applicable to e.g. SQCD

Single modulus case (as like KKLT)

$$K = -3M_P^2 \ln\left(T + \overline{T}\right)$$

$$V(T + \overline{T}) = e^{K/M_P^2}\left(K^{ij} D_i W D_{\bar{j}} \overline{W} - \frac{3}{M_p^2}|W|^2\right)$$

→ *no potential generated*

Comments on C4 axion

Generating the potential? ⟹ more complicated setup with multiple moduli

[10 Dine-Festuccia-Kehayias-Wu]

$$K = -\frac{3M_P^2}{2}\ln\left[(T_1+\overline{T}_1)(T_2+\overline{T}_2)\right] + K_X(X,X^\dagger)$$

$$W = W_0 - Ae^{-(T_1+T_2)/b} + fX$$

X : SUSY breaking field

- Heavy moduli multiplet: $\rho = T_1 + T_2$ ⟹ integrated out
- Light multiplet: $\psi = T_1 - T_2$ ⟹ includes axion!

Scales of axion: $m_\psi \sim e^{-\rho} M_P$ suppressed!

However, the potential is nonperturvatively generated...

⟹ requires 10^4 axions (cycles) for quintessence

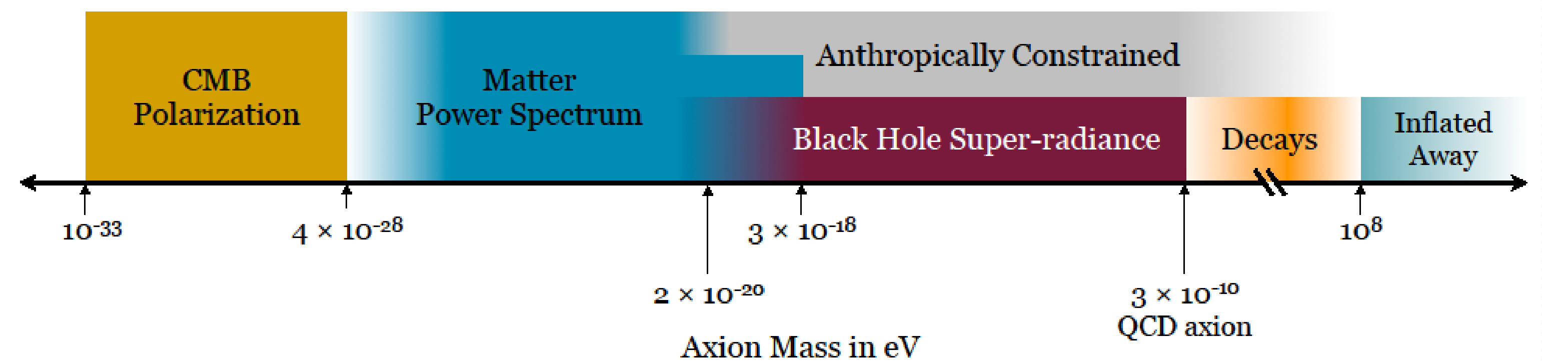
Instead, applicable to strong CP problem with fine-tuning SUSY breaking scale f

Rotation Angle of CMB Polarization

Rotation of the CMB polarization

String Axiverse map

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



Naively estimated effective mass scale

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

→ 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

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

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 $\phi_0 \sim 100 M_P$

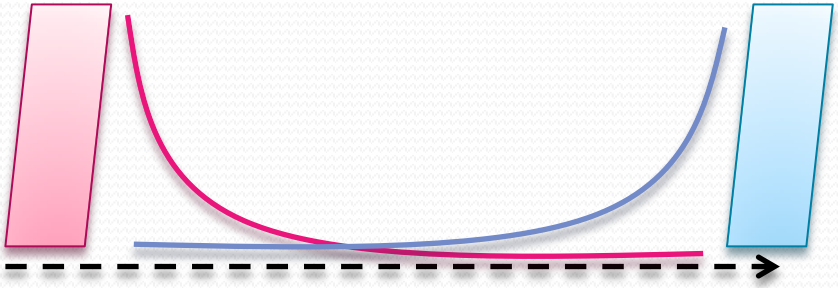
without violating any other bounds

Discussions

Other comments

Light particles

Large warping required in our model ⇒ many light particles



As like in RS II, wave-functions are well-localized 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.

Moduli problems

Reheating for BBN: $T_r \gtrsim 10\,\mathrm{MeV}$

Boltzmann eq. suggests

$$T_r \sim \sqrt{M_P \Gamma_\phi}, \quad \Gamma_\phi \sim \frac{m_{3/2}^3}{M_P}$$

→ $m_{3/2} \gtrsim 100\,\mathrm{TeV}$

→ $M_{\mathrm{SB}} \sim \sqrt{m_{3/2} M_P} \sim 10^{11}\,\mathrm{GeV}$

In our model, if $M_{SB} \gtrsim 1\,\mathrm{TeV}$

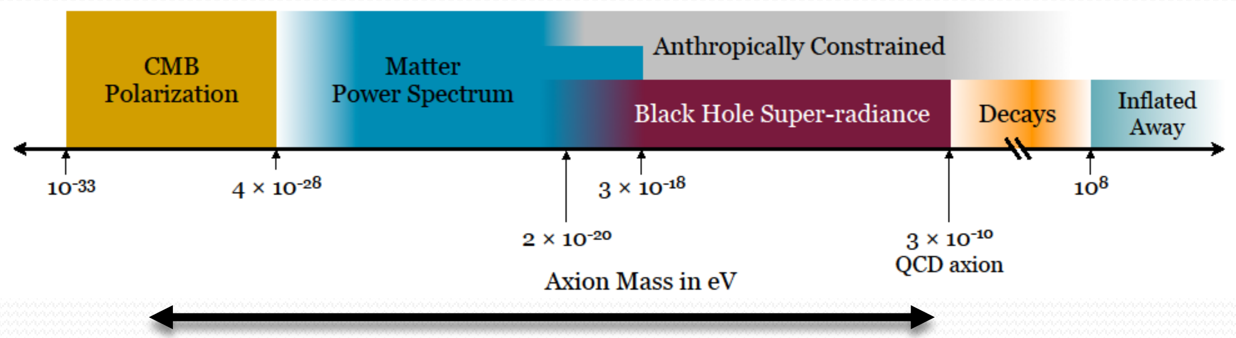
→ the brane-anti brane potential from moduli stabilization dominates

But, SUSY breaking models with lower energy?

→ requires additional setups, including thermal inflation,
extra symmetries, helicity suppression and etc.

QCD axion and U(1) axion

Hierarchy between QCD axion and U(1) axion



U(1) axion: related to C2 and two-cycles

QCD axion: presumably originated from C4 and four-cycles

How to explain the scale hierarchy $m_{\rm QCD}/m_{U(1)} \sim 10^{-23}$?

- Where D7-brane lives?
- GUT model with some other mechanism?

Comments on 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,

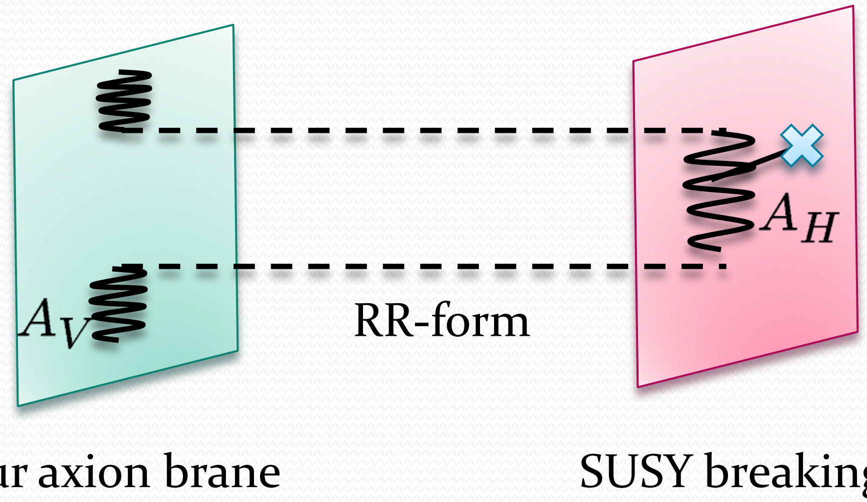
SU(2) x SU(2) invariant non-chiral supermultiplet in Klebanov-Witten (Klevnov-Strassler) theory

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

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

Higher form mediation

[07 Verlinde-Wang-Wijnholt-Yavin]



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

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

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

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

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

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

doesn't cause serious contributions