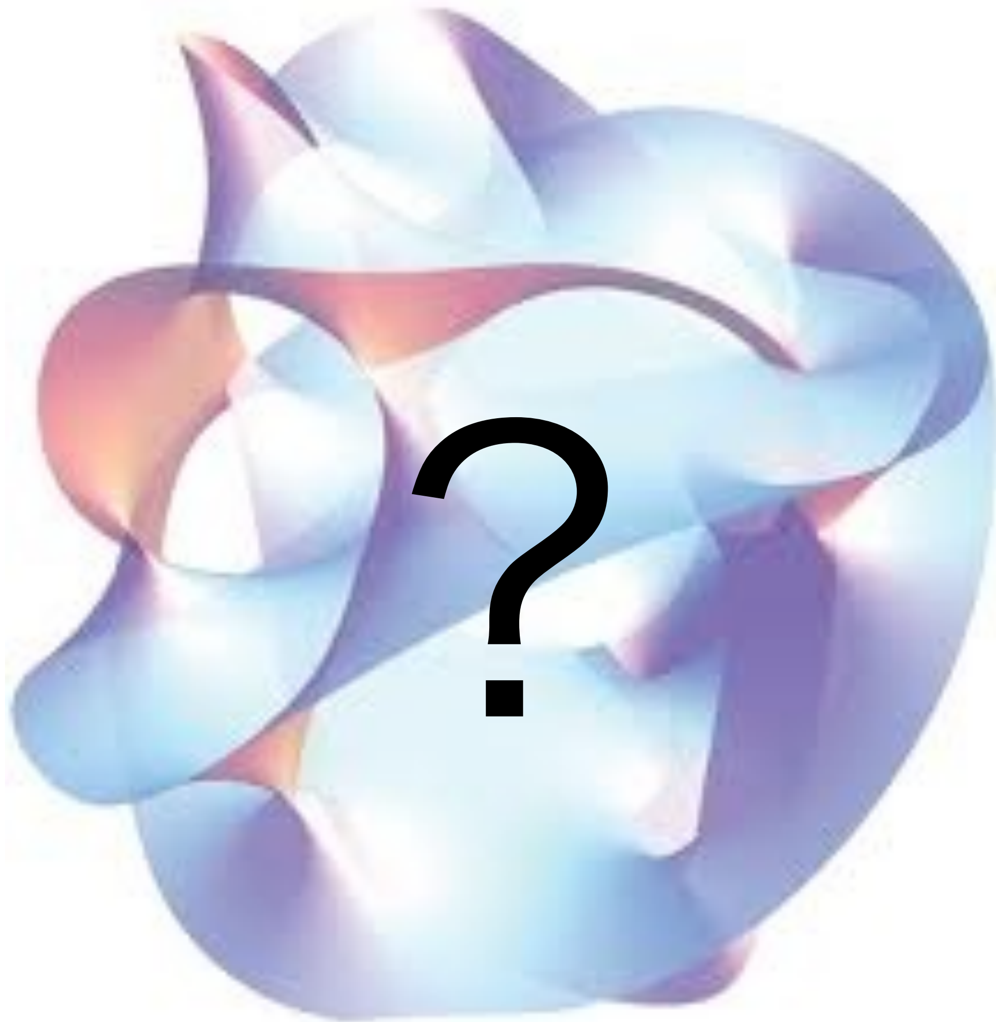
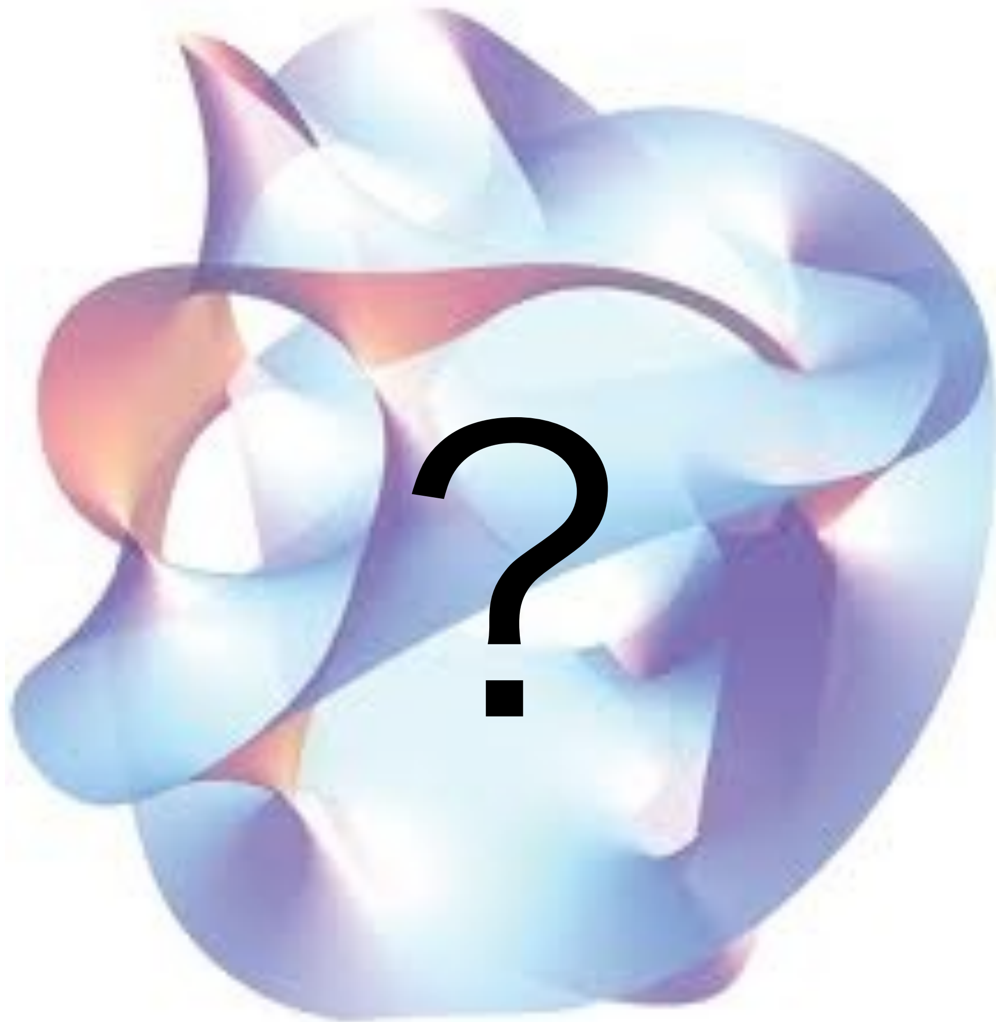
Moduli-induced axion problem

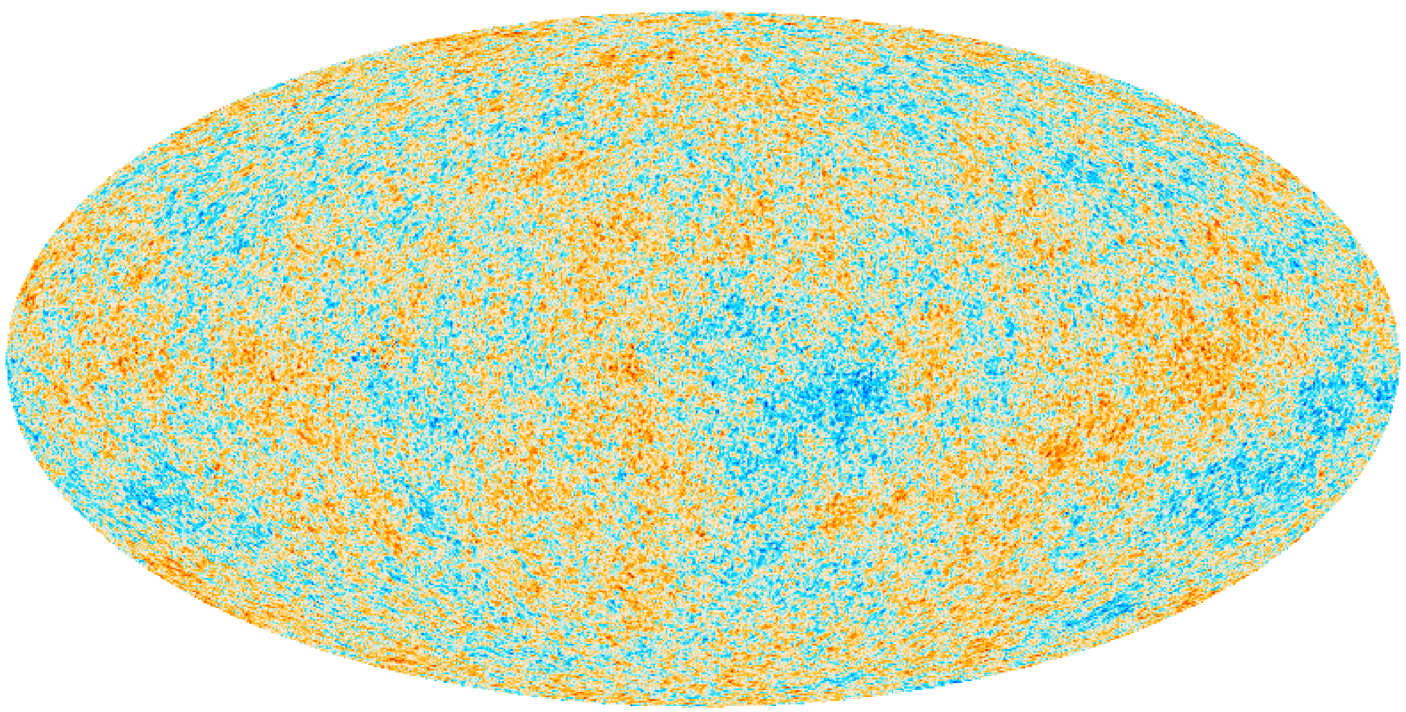
Kazunori Nakayama (University of Tokyo)

T.Higaki, KN, F.Takahashi, JHEP1307,005 (2013) [1304.7987]

SUSY2013 @ ICTP, Trieste, Italy (2013/8/26)







What we have shown :

- Kahler moduli : $T_j = \tau_j + i a_j$
  moduli axion

- Moduli decays into very light axion :

$$\tau_j \to 2 a_j$$

- Too much axionic dark radiation
  in light of PLANCK

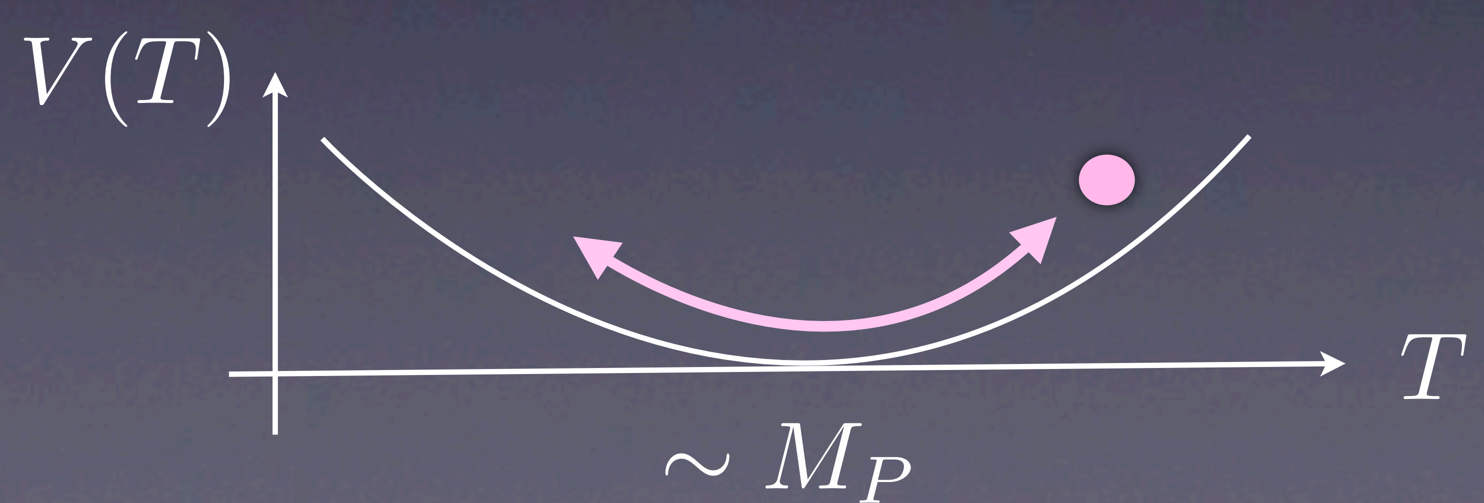
Brief review of moduli problem

Moduli Problem

[Coughlan et al. (1983), Ellis et al. (1986), Banks et al. (1993), de Carlos et al. (1993)]

- Moduli = Light scalar field in compactification of extra dimensions in String theory

- At H~m, moduli begins to oscillate around minimum with typical amplitude $\sim M_P$



Moduli Problem

- Moduli abundance

$$\frac{\rho_T}{s} = \frac{1}{8} T_R \left(\frac{z_i}{M_P}\right)^2 \sim 10^5 \mathrm{GeV} \left(\frac{T_R}{10^6 \mathrm{GeV}}\right) \left(\frac{z_i}{M_P}\right)^2$$

T_R : reheat temperature
z_i : moduli initial amplitude

- Moduli lifetime

$$\tau_T \sim \left(\frac{m_T^3}{M_P^2}\right)^{-1} \sim 10^4 \mathrm{sec} \left(\frac{1 \mathrm{TeV}}{m_T}\right)^3$$

- Big bang nucleosynthesis constraint

[Kawasaki, Kohri, Moroi (2004)]

$$\frac{\rho_T}{s} \lesssim 10^{-14} \mathrm{GeV}$$

Moduli Problem

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...at temperature

$\ldots_i$: moduli initial amplitude

- Moduli lifeti...

$$\ldots P) \sim 10^4 \mathrm{sec} \left(\frac{1 \mathrm{TeV}}{m_T} \right)^3$$

Moduli problem

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Heavy moduli ?

- Moduli decay before BBN $(m_T \gg \mathcal{O}(10)\,\mathrm{TeV})$
    - *Heavy SUSY moduli* (e.g., KKLT) $m_T \gg m_{3/2}$
    - *Heavy non-SUSY moduli* $m_T \lesssim m_{3/2}$

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    Moduli decay into gravitino

    → Moduli-induced gravitino problem

    [Endo, Hamaguchi, Takahashi (2006), Nakamura, Yamaguchi (2006)]

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    [Cicoli, Conlon, Quevedo (2012), Higaki, Takahashi (2012), Higaki, KN, Takahashi (2013)]

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Moduli-induced axion problem

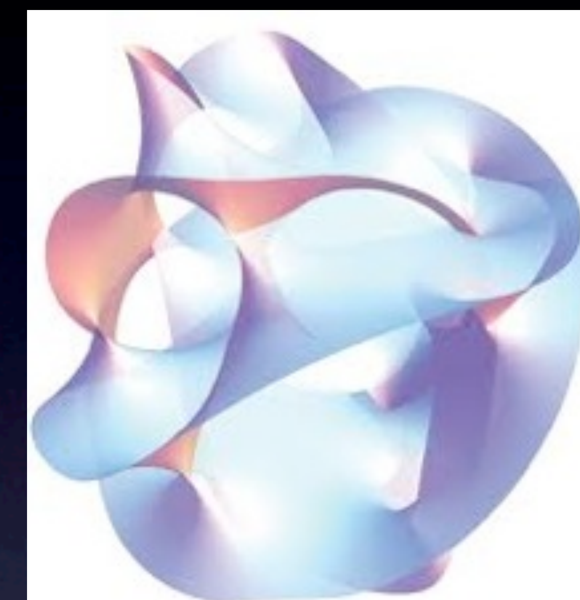
T.Higaki, KN, F.Takahashi, 1304.7987

Moduli in typeIIB string

- Kahler moduli : T

  Shift symmetry : $T \rightarrow T + i\alpha$

  cf) 10d gauge symmetry $C_4 \rightarrow C_4 + d\Lambda$



- Kahler potential : $K = K(T + T^\dagger)$

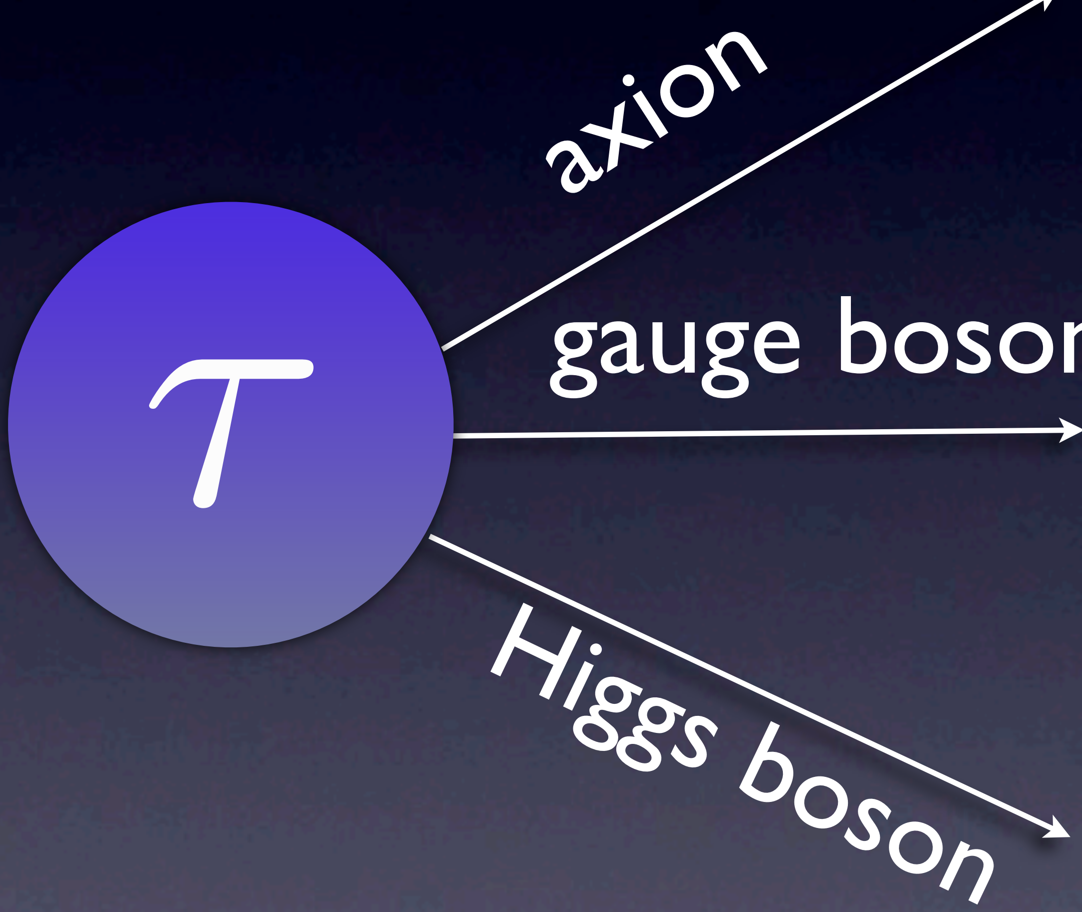
$$T - \langle T \rangle \equiv \frac{\tau + ia}{\sqrt{2K_{TT}}}$$

axion

- Suppose that moduli stabilization does not give axion mass

General analysis on moduli decay

T.Higaki, KN, F.Takahashi, 1304.7987



$$\Gamma(\tau \to 2a) = \frac{1}{64\pi} \frac{K_{TTT}^2}{K_{TT}^3} m_\tau^3$$

$$\Gamma(\tau \to A_\mu A_\mu) = \frac{N_g}{128\pi} \frac{|\partial_T f_{\rm vis}|^2}{({\rm Re} f_{\rm vis})^2} \frac{m_\tau^3}{K_{TT}}$$

$f_{\rm vis}(T)$: gauge kinetic function

$$\Gamma(\tau \to HH) \simeq \frac{1}{8\pi} \frac{g_T^2}{K_{TT} Z_u Z_d} m_\tau^3$$

$$K \supset g(T + T^\dagger)(H_u H_d + {\rm h.c.})$$

Note : decay into their superpartners can also be sizable

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Branching ratio into axion (B_a) is generally O(1)

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Planck constraint on Neff

- Radiation energy density $\rho_{\rm rad} = \left[1 + \frac{7}{8} N_{\rm eff} \left(\frac{4}{11}\right)^{4/3}\right] \rho_\gamma$
- CMB constraint: $N_{\rm eff} = 3.36^{+0.68}_{-0.64}$ @ 95%CL

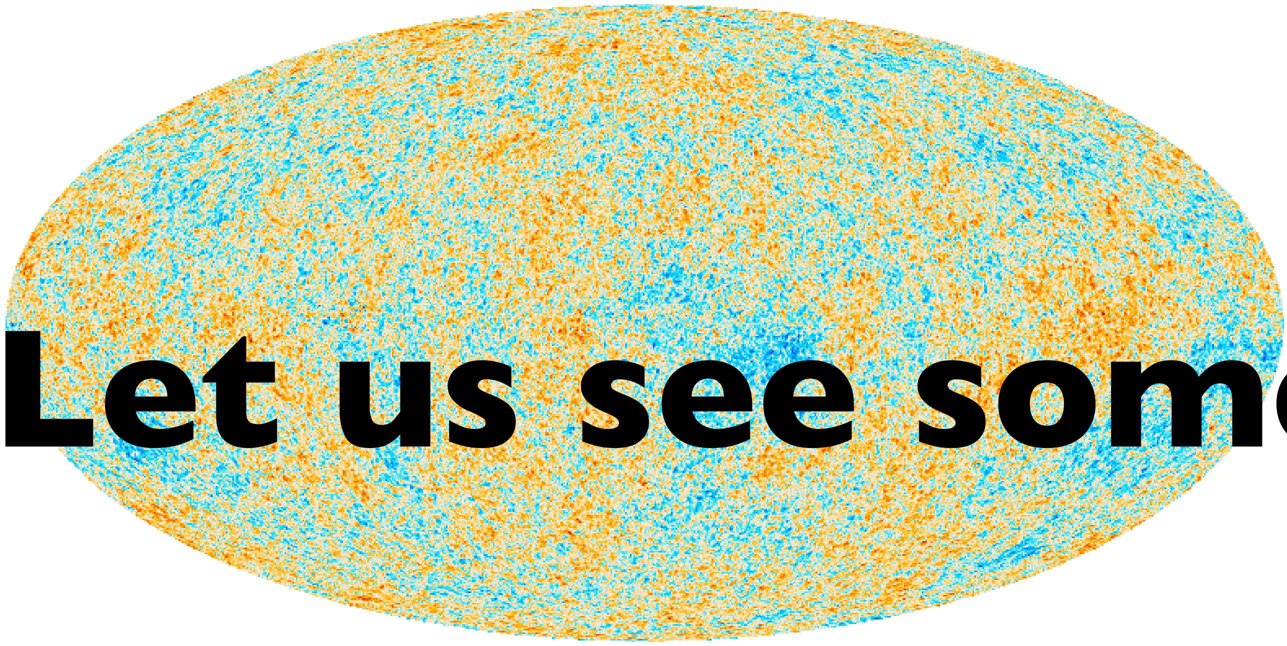
Planck+WMAP pol+ high l

[Ade et al. 1303.5076]

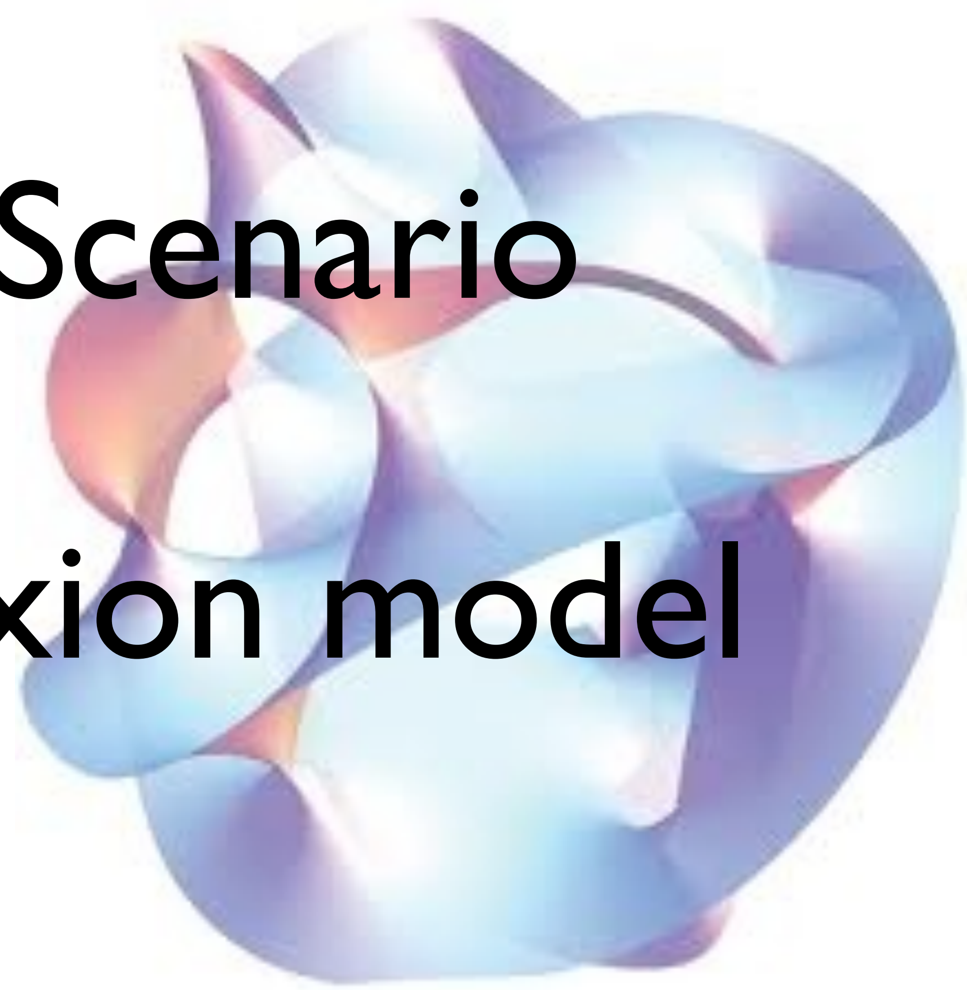
- Axion dark radiation abundance:

$$\Delta N_{\rm eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_d)}\right)^{1/3} \frac{B_a}{1-B_a} \longrightarrow B_a \lesssim 0.2$$

⟶ Constraint on moduli stabilization model



Let us see some examples.



1. Large Volume Scenario

2. KKLT String axion model

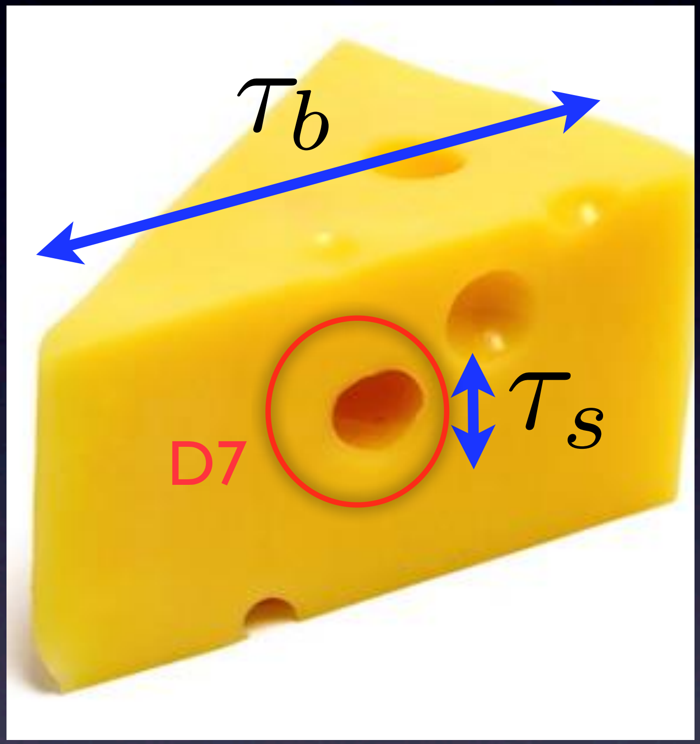
Ex 1) Large Volume Scenario

[Balasubramanian et al. (2005), Conlon, Quevedo, Suruliz (2005)]

- Swiss-Cheeze CY: $\mathcal{V} = \mathcal{V}_0 - \mathcal{V}_{\text{hole}}$

  The simplest : $\mathcal{V}_0 = (T_b + T_b^\dagger)^{3/2}$

  $\mathcal{V}_{\text{hole}} = (T_s + T_s^\dagger)^{3/2}$



- Kahler and Superpotential

$$K = -2\ln(\mathcal{V} + \xi)$$

$$W = W_0 + A_s e^{-2\pi T_s}$$

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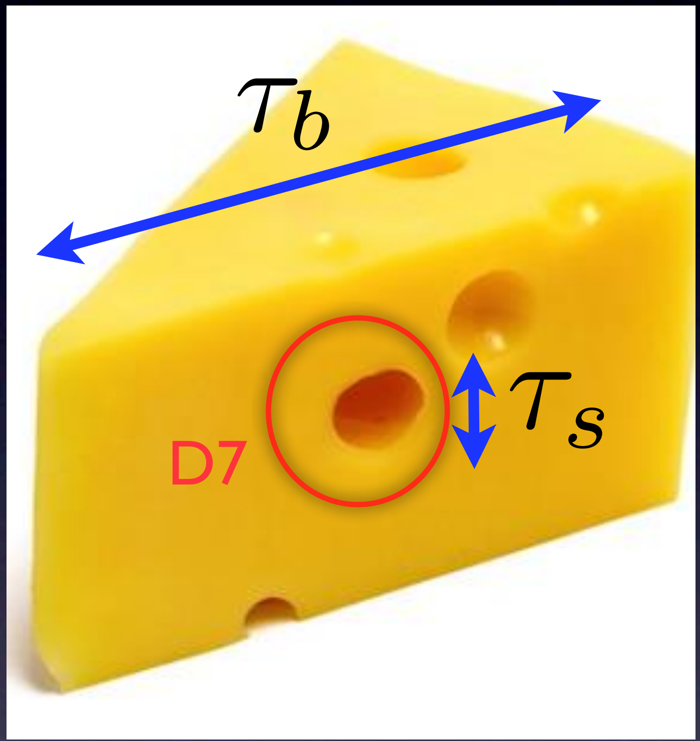

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Stabilized a la KKLT

$m_{\tau_s} \sim m_{a_s}$

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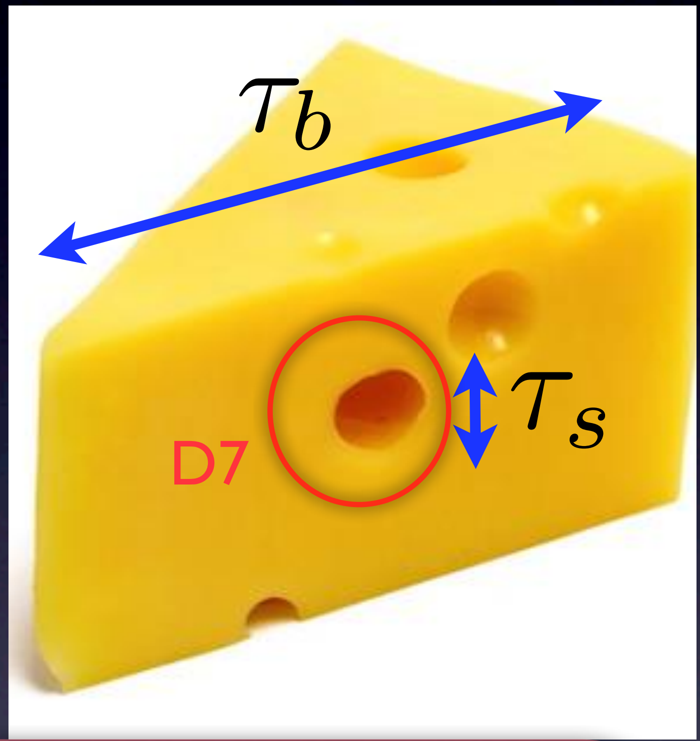

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Stabilized by alpha' correction.

Volume axion $(\mathrm{Im}\, T_b = a_b)$ remains massless

Stabilized a la KKLT

$m_{\tau_s} \sim m_{a_s}$

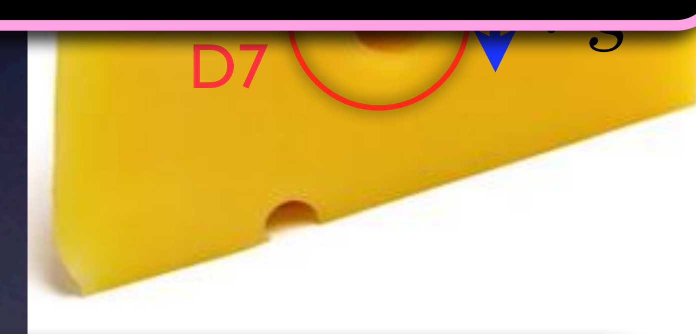
2013年8月24日土曜日

$$V = \frac{\sqrt{\tau_s} b_s^2 |A_s|^2 e^{-2b_s\tau_s}}{\mathcal{V}} - \frac{b_s |A_s W_0| \tau_s e^{-b_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}$$

Minimization

$$\mathcal{V} \sim \tau_b^{3/2} \sim e^{2\pi\tau_s} \sim e^{\frac{2\pi\xi^{2/3}}{g_s}} \gg 1$$

Large Volume Scenario (LVS)



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Stabilized a la KKLT

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- Mass scales
  - Gravitino mass $m_{3/2} \sim e^{K/2} W_0 \sim \frac{1}{\mathcal{V}}$ for $|W_0| \sim O(1)$
  - Moduli masses $m_{\tau_s} \sim m_{a_s} \sim \frac{1}{\mathcal{V}}$

    $m_{\tau_b} \sim \frac{1}{\mathcal{V}^{3/2}}$: Lightest modulus

    $m_{a_b} = 0$: Axion
  - Soft mass (sequestered scenario) $m_{\text{soft}} \sim \frac{1}{\mathcal{V}^2}$

(Moduli-matter coupling : $K_{\text{MSSM}} = \frac{|\Phi_i|^2 + (zH_u H_d + \text{h.c.})}{(T_b + T_b^\dagger)}$)

E.g., $\mathcal{V} \sim 10^7 \longrightarrow$ $m_{3/2} \sim 10^{11}\ \text{GeV}$, $m_{\tau_b} \sim 10^7\ \text{GeV}$

- Moduli decay rate [Cicoli, Conlon, Quevedo (2012), Higaki, Takahashi (2012) Angus, Conlon, Haisch, Powell (2013)]

  - Two axion : $\tau_b \to 2a$ $\quad \Gamma_a = \frac{1}{48\pi} \frac{m_{\tau_b}^3}{M_P^2}$

  - Two Higgs : $\tau_b \to 2H$ $\quad \Gamma_H = \frac{z^2}{24\pi} \frac{m_{\tau_b}^3}{M_P^2}$

$\longrightarrow$ Branching ratio into axion: $B_a = \frac{1}{1+2z^2}$

Independent of moduli mass

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Independent of moduli mass

Constraint : $B_a < 0.2 \longrightarrow \begin{cases} z \gtrsim 2 \\ \text{Many Higgs doublets} \end{cases}$

cf. z=1 if Higgs has shift symmetry [Hebecker et al. (2012)]

Ex 2) QCD axion in KKLT

[J.Conlon (2006), K.Choi, K.S.Jeong (2006)]

- String theoretic QCD axion model

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$$K = -2\ln\mathcal{V}$$

$$\mathcal{V} = (T_0 + T_0^\dagger)^{3/2} - \kappa_1(T_1 + T_1^\dagger)^{3/2} - \kappa_2(T_2 + T_2^\dagger)^{3/2}$$

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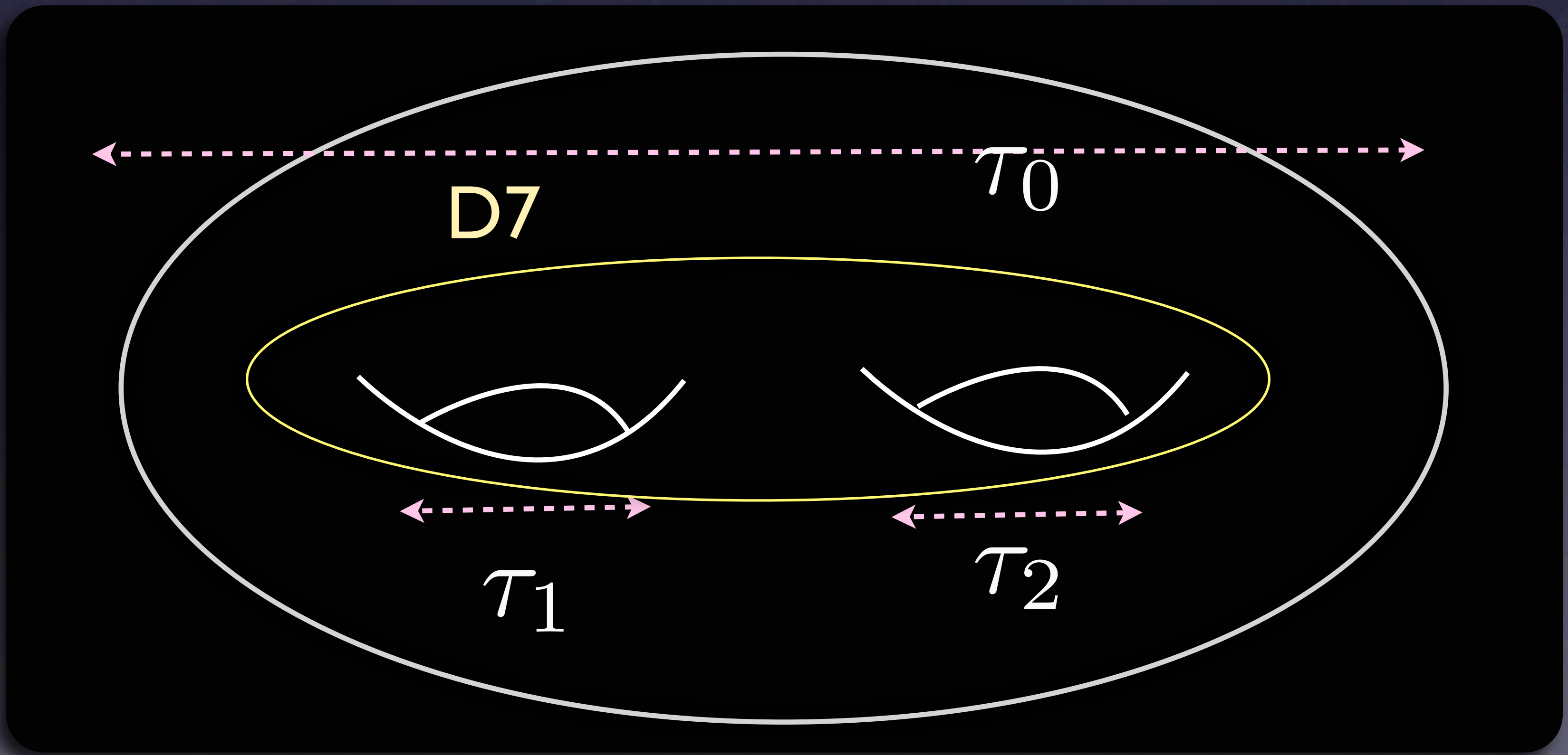

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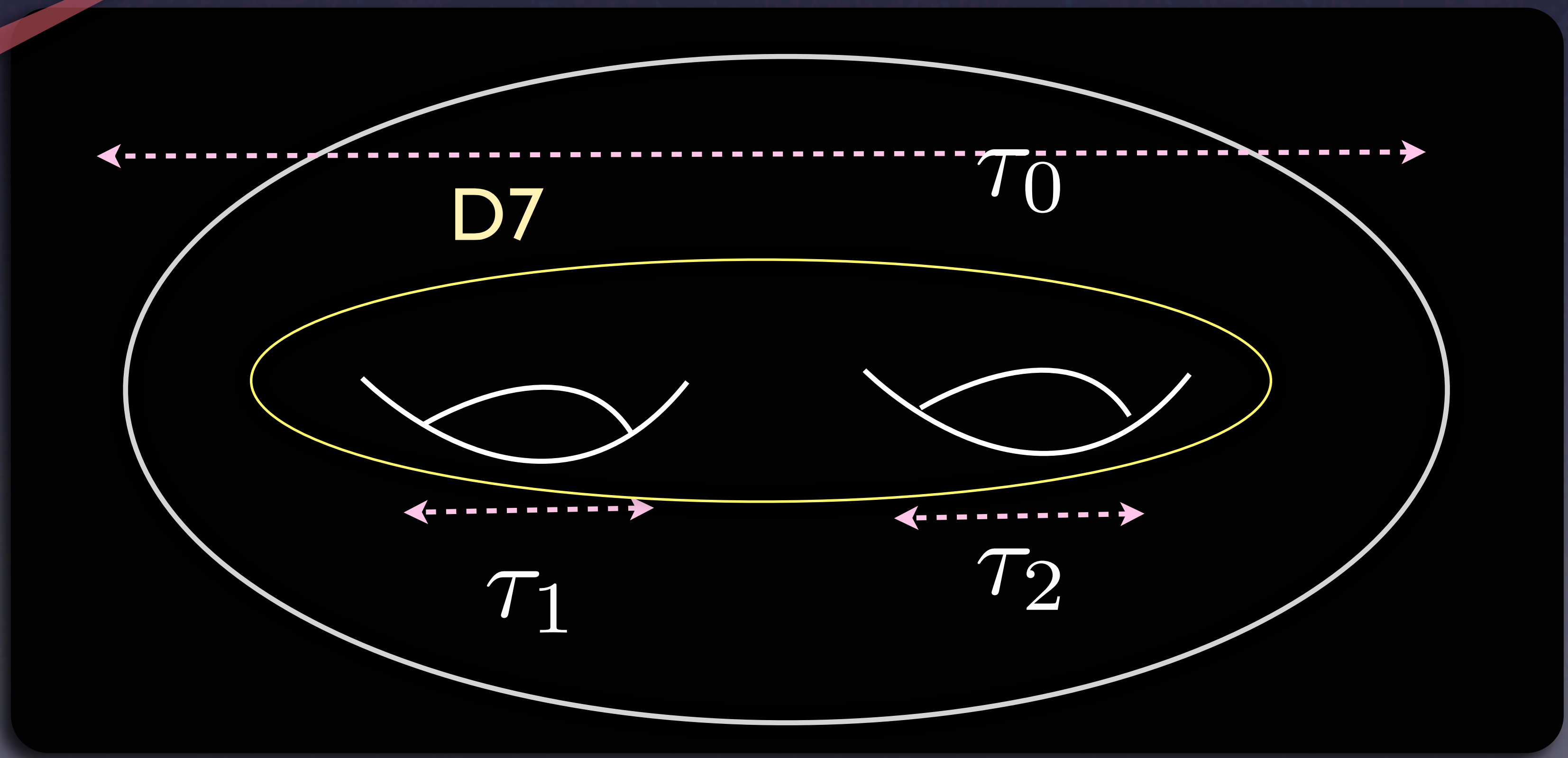

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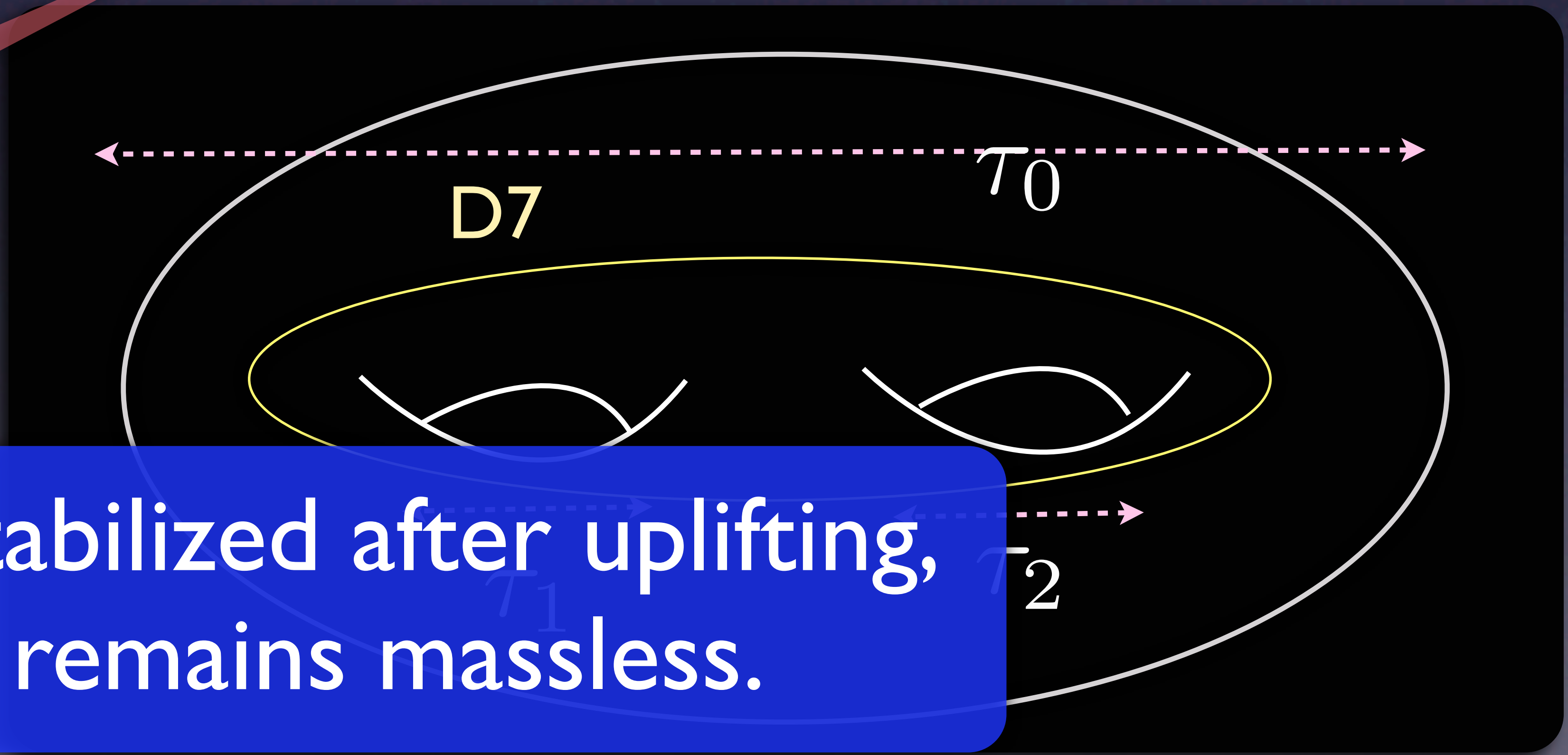


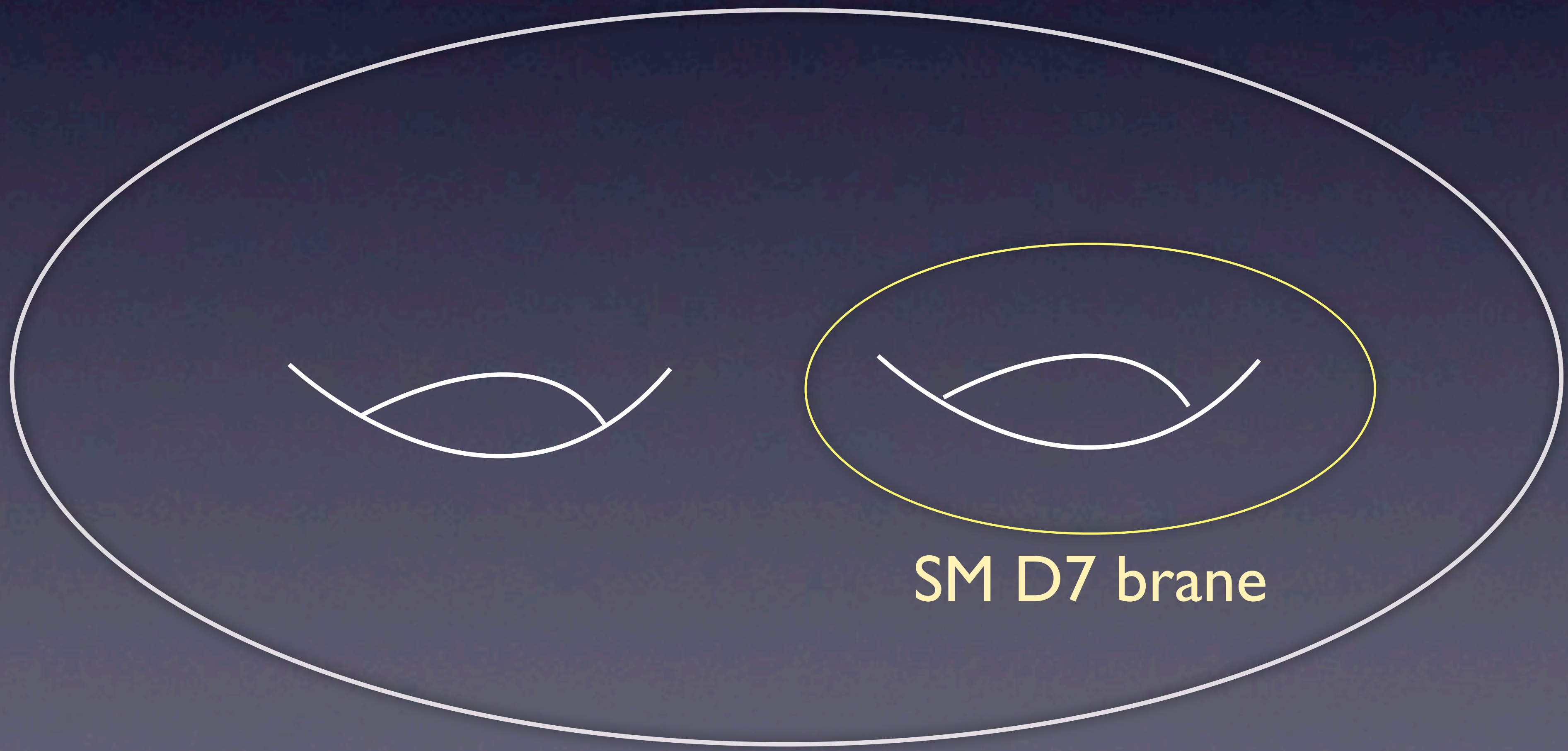
$\mathcal{A} \equiv nT_1 - T_2$ is stabilized after uplifting, while $\mathrm{Im}\mathcal{A} \equiv a$ remains massless.

- SM brane wraps cycle T2

SM gauge kinetic function : $f_{\mathrm{vis}} = \dfrac{T_2}{4\pi}$

$$\mathcal{A} \equiv nT_1 - T_2 \equiv s + ia$$

$$\mathcal{L} = \int d^2\theta f_{\mathrm{vis}} \mathcal{W}_a \mathcal{W}^a + \mathrm{h.c.} \sim \frac{s}{\tau_2} G^a_{\mu\nu} G^{\mu\nu a} + \frac{a}{\tau_2} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$



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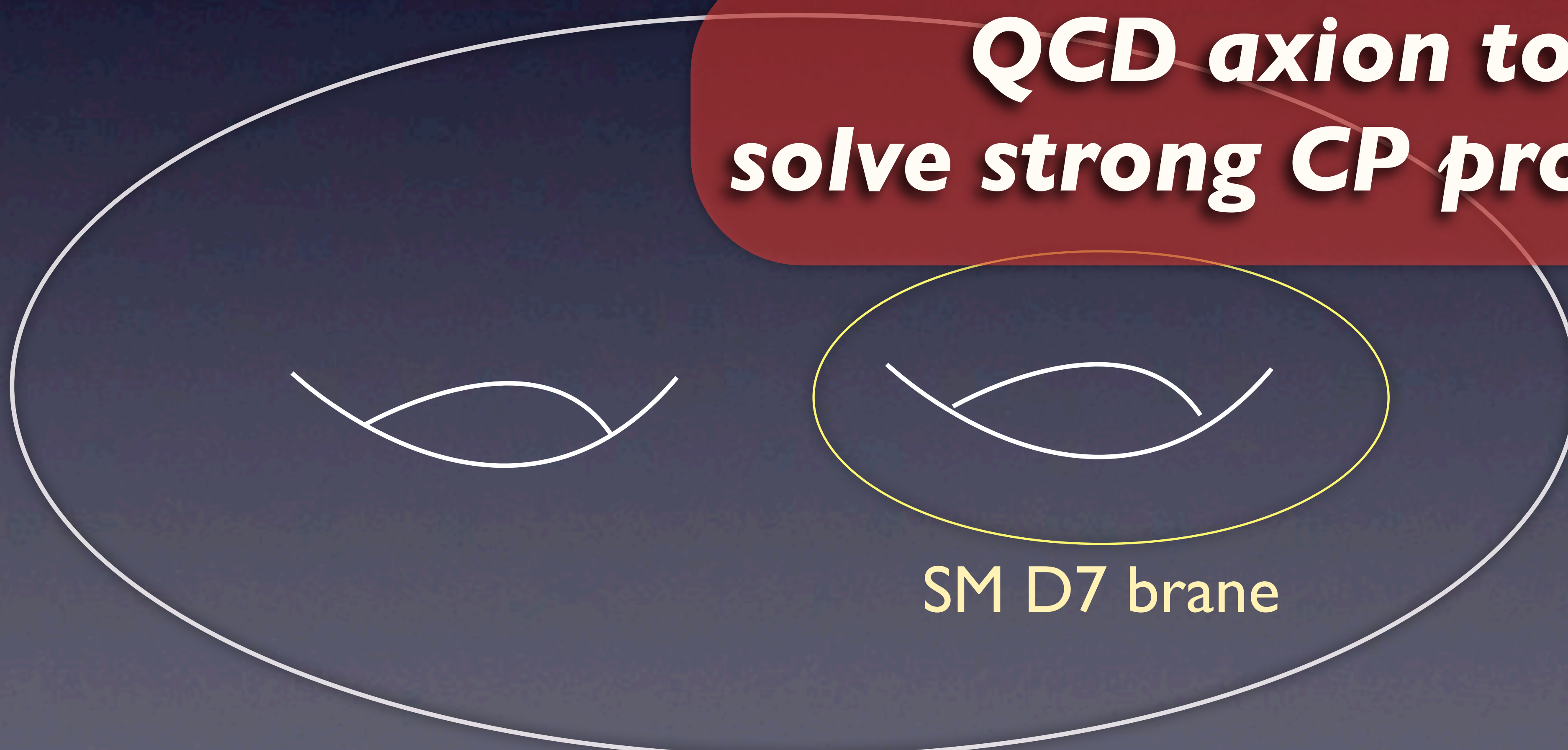
QCD axion to solve strong CP problem



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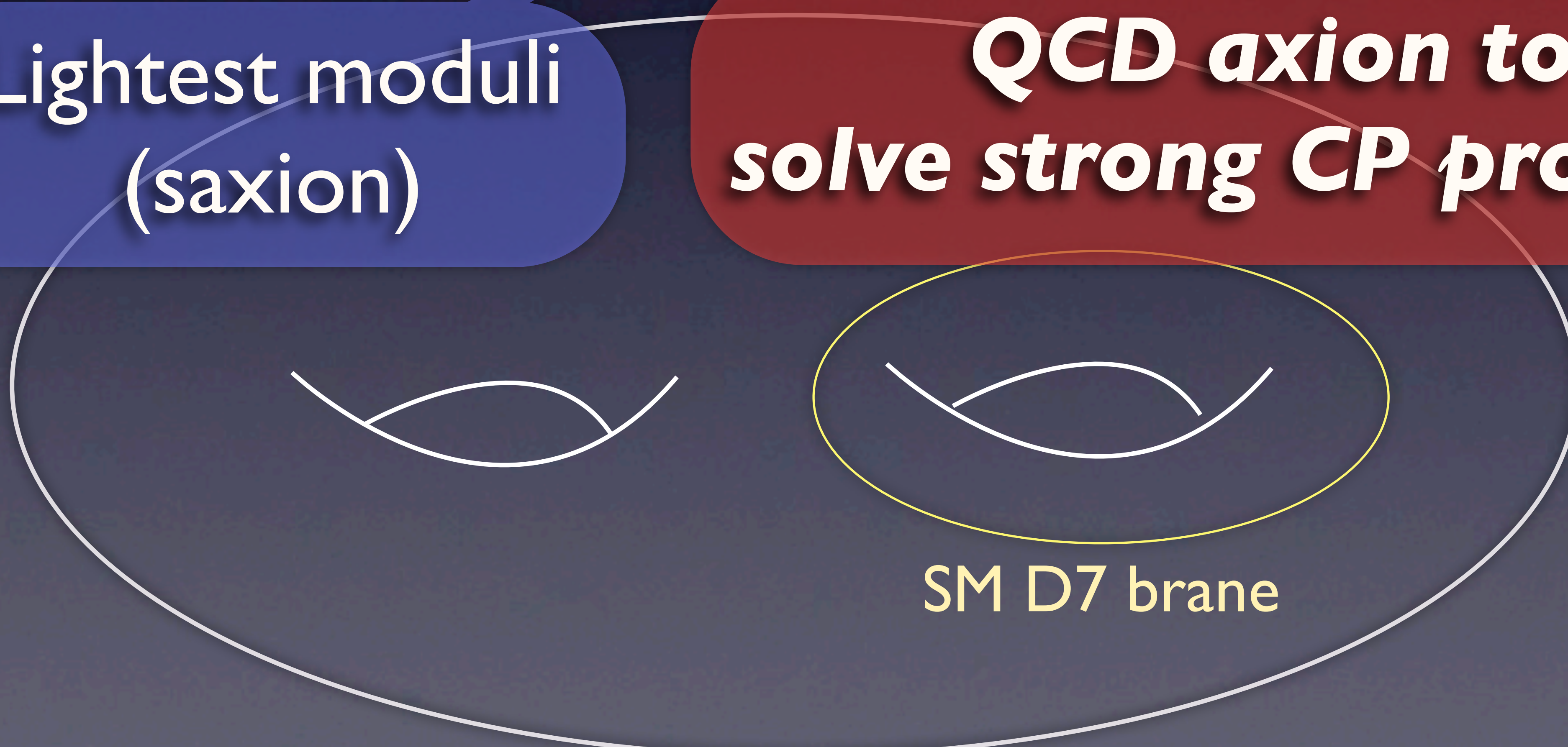
Lightest moduli (saxion)

QCD axion to solve strong CP problem



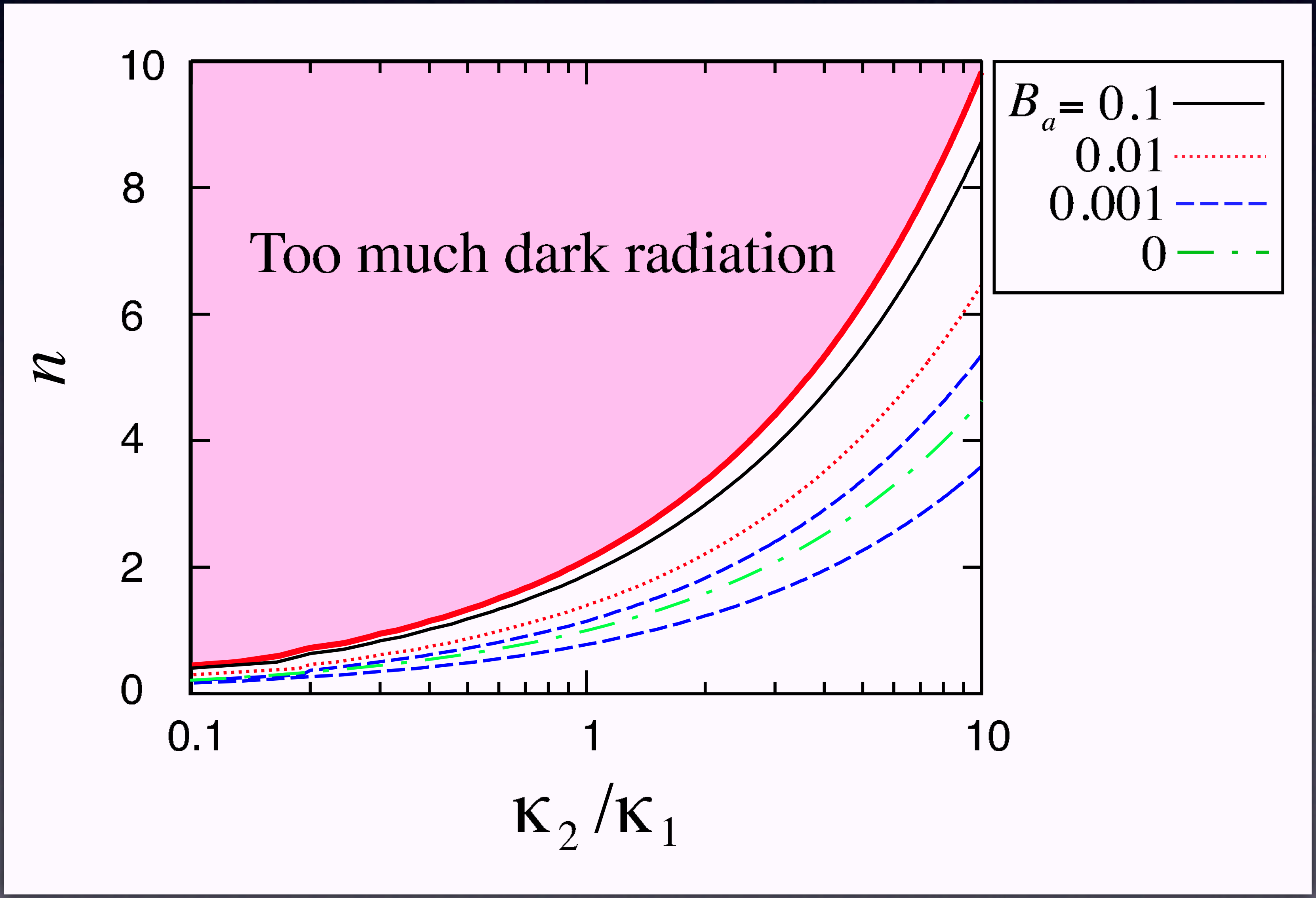
- Moduli (Saxion) decay rate

$$M_s^3 \equiv \frac{1}{\sqrt{2}}\left(\frac{\sqrt{n^3\kappa_1^2+\kappa_2^2}}{n^3\kappa_1^2}\right)\frac{\mathcal{V}}{\phi^{3/2}}m_s^3$$

  - Two axion : $\Gamma_a \simeq \frac{(n^2\kappa_1^2-\kappa_2^2)^2}{768\pi\kappa_2^3}\frac{M_s^3}{M_P^2}$

$$m_s \sim \mathcal{O}(10^3)\ \mathrm{TeV}$$

  - Gauge boson : $\Gamma_g \simeq \frac{\kappa_2}{8\pi}\frac{M_s^3}{M_P^2}$: Not loop suppressed



Decay into gluon is sizable in contrast to (usual) saxion decay in SUSY axion model.

[T.Higaki, KN, F.Takahashi, 1304.7987]

Detecting/constraining axionic dark radiation

- The presence of axionic dark radiation seems to be ubiquitous in string theory $\Delta N_{\rm eff} \gtrsim \mathcal{O}(0.1)$
- Can we probe it?
  - Axion conversion into X-ray photon in galaxy cluster [J.Conlon, M.C.D.Marsh, 1305.3603]
  - Axion-photon conversion in the early Universe under primordial magnetic field [T.Higaki, KN, F.Takahashi, 1306.6518]
  - Any other idea?

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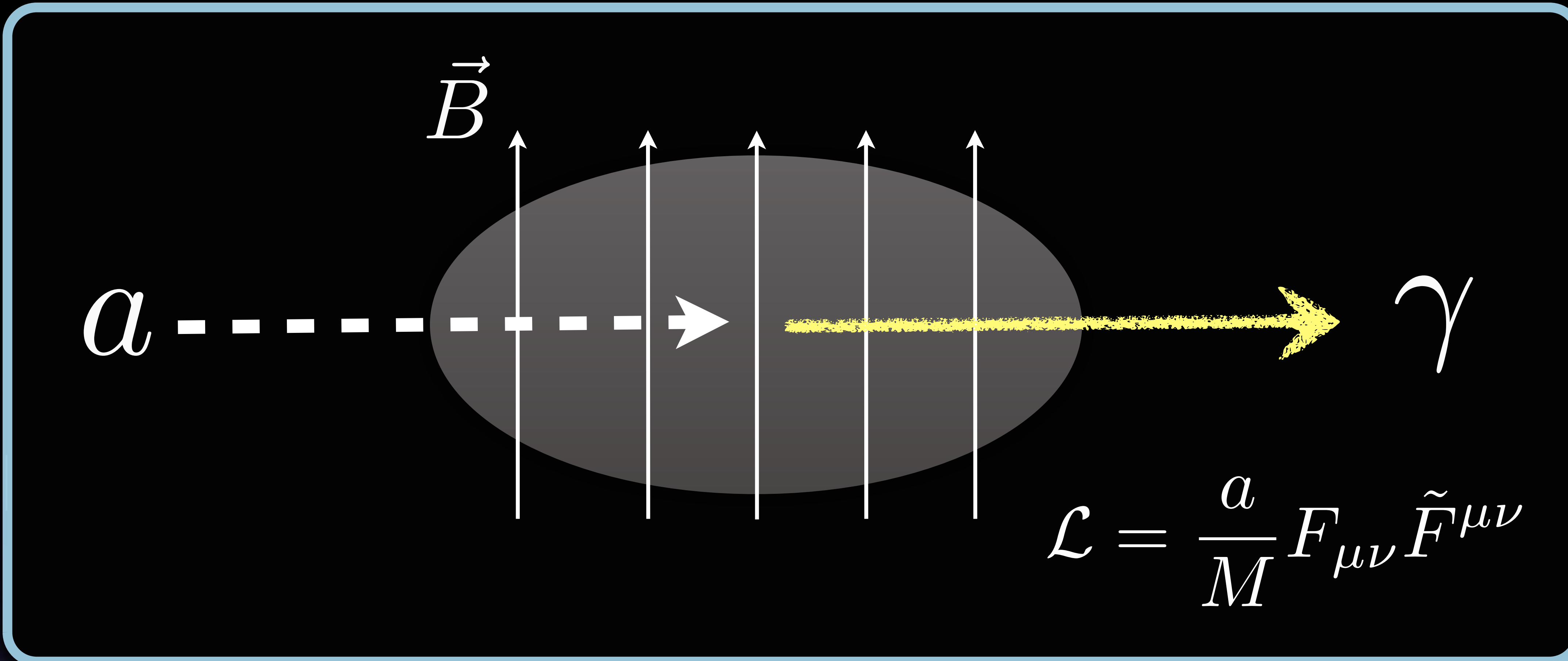

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Summary

- Light axions often appear after moduli stabilization
- Moduli branch into axion is generically O(1)

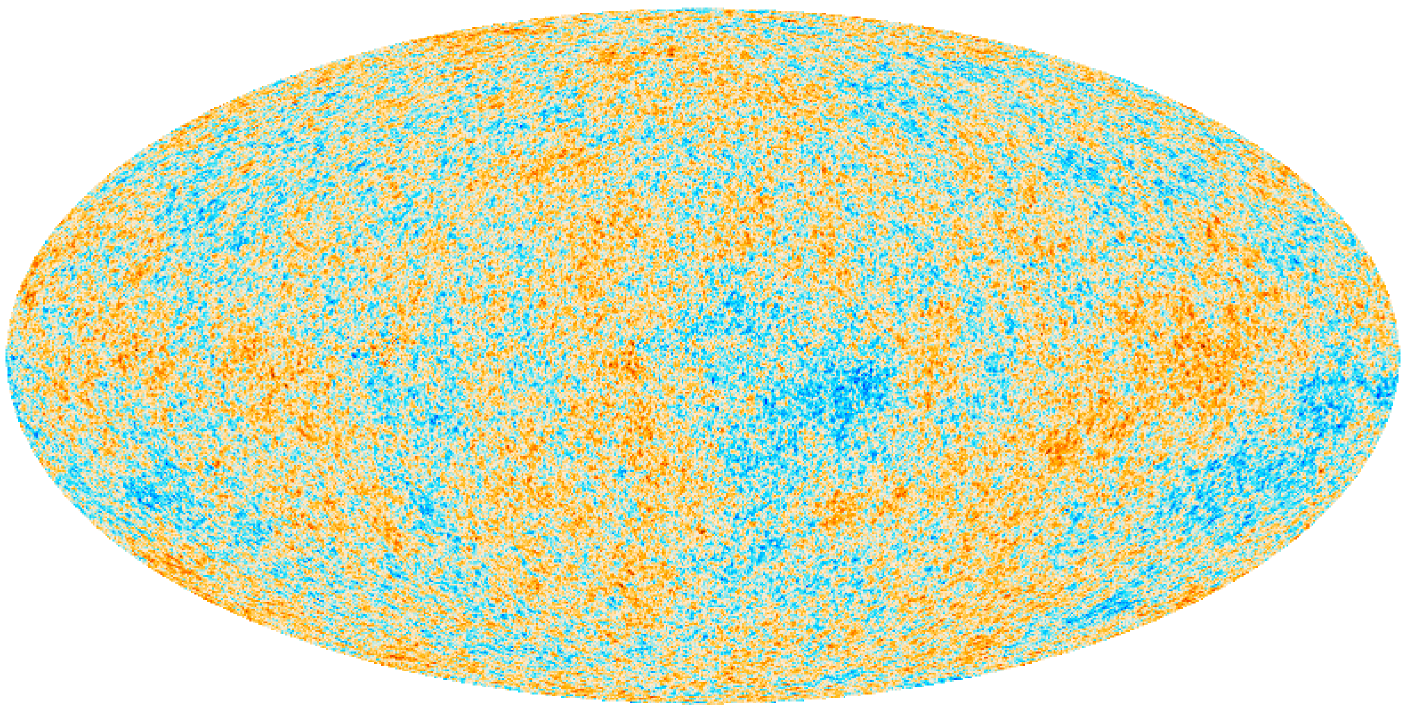
$\longleftrightarrow$ Planck constraint : $B_a \lesssim 0.2$

- The branch does not depend on moduli mass

The problem exists even for heavy moduli

$(m_T \gg \mathcal{O}(10)\,\mathrm{TeV})$

"Moduli-induced axion problem"



Cosmological test of compactification model

Appendix

Possible Solutions to moduli problem

- 1. Thermal inflation for diluting moduli

[Lyth, Stewart (1996)]

→ Dilution of baryon asymmetry
Domain wall problem

- 2. Adiabatic suppression mechanism [A.Linde (1996)]

$$V \sim c^2 H^2 T^2 + m_T^2 (T - T_0)^2 \qquad c \gg 1$$

→ Suppression is not exponential but power in c

High inflation scale & low reheat temp. is needed.

[KN, F.Takahashi, T.Yanagida (2011)]

Moduli abundance

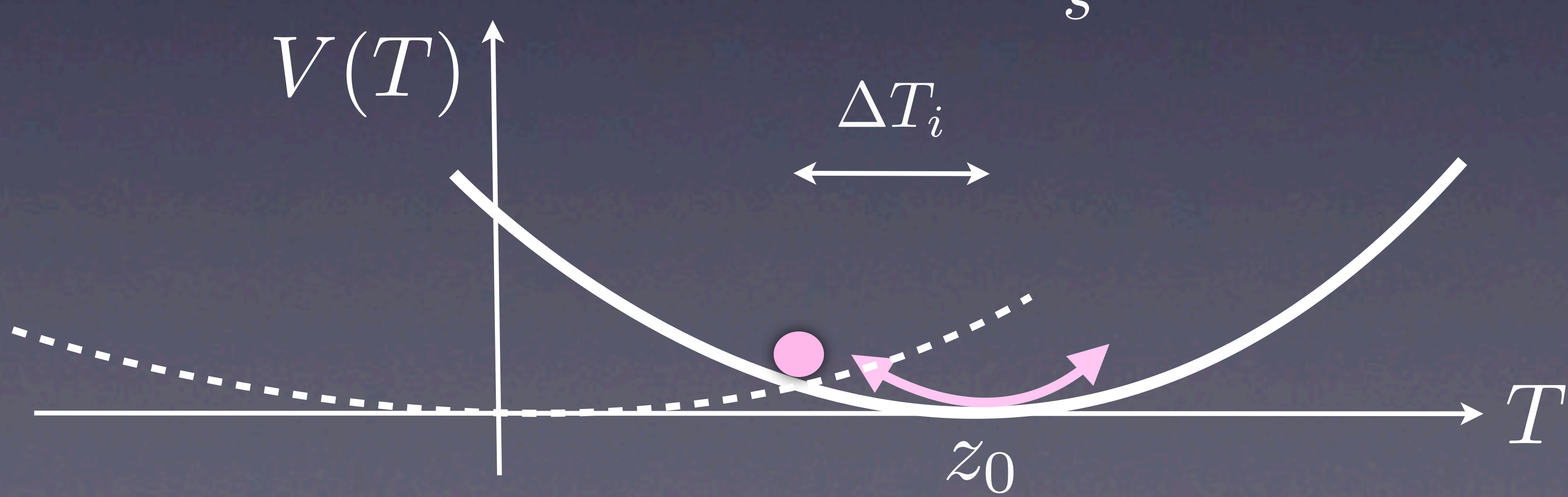
$$V(T) = cH^2T^2 + m_T^2(T - z_0)^2 \quad (c \sim \mathcal{O}(1))$$

[For $c \gg 1$, see KN, Takahashi, Yanagida, 1109.2073]

- $H_{\rm inf} \gg m_T$: $\Delta T_i \sim z_0 \quad \longrightarrow \quad \frac{\rho_T}{s} \sim \frac{1}{8} T_R \left(\frac{z_0}{M_P}\right)^2$
- $H_{\rm inf} \ll m_T$: $\Delta T_i \sim \frac{H_{\rm inf}^2}{m_T^2} z_0 \quad \longrightarrow \quad \frac{\rho_T}{s} \sim \frac{1}{8} T_R \left(\frac{z_0}{M_P}\right)^2 \left(\frac{H_{\rm inf}}{m_T}\right)^2 \quad (m_{\rm inf} \gg m_T)$

  [cf. Kallosh-Linde bound]

  $\searrow \quad \frac{\rho_T}{s} \sim 0 \quad (m_{\rm inf} \ll m_T)$



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T.Higaki, KN, F.Takahashi, 1304.7987

- Moduli T $\quad K = K(T + T^\dagger)$
- Canonically normalized moduli & axion $\quad T - \langle T \rangle \equiv \frac{\tau + ia}{\sqrt{2K_{TT}}}$
  - Moduli decay into axion pair

$$\mathcal{L} = \frac{K_{TTT}}{\sqrt{2}K_{TT}^{3/2}}\tau(\partial a)^2 \longrightarrow \Gamma(\tau \to 2a) = \frac{1}{64\pi}\frac{K_{TTT}^2}{K_{TT}^3}m_\tau^3$$

  - Moduli decay into axino pair (if kinematically allowed)

$$\mathcal{L} = \frac{1}{\sqrt{2}}\frac{K_{TTT}}{K_{TT}^{3/2}}\tau\left[-i\tilde{a}^\dagger\bar{\sigma}_\mu\partial^\mu\tilde{a} + i(\partial_\mu\tilde{a}^\dagger)\bar{\sigma}^\mu\tilde{a}\right]$$

$$\longrightarrow \Gamma(\tau \to 2\tilde{a}) = \frac{1}{8\pi}\frac{K_{TTT}^2}{K_{TT}^3}m_{\tilde{a}}^2 m_\tau$$

General analysis on moduli decay

T.Higaki, KN, F.Takahashi, 1304.7987

- Coupling to MSSM sector
  - Gauge kinetic function $f_{\rm vis}(T)$
    - Moduli decay into gauge boson pair

$$\mathcal{L} = -\frac{1}{4\sqrt{2K_{TT}}({\rm Re} f_{\rm vis})}\left({\rm Re}(\partial_T f_{\rm vis})\tau F^a_{\mu\nu}F^{\mu\nu a} - {\rm Im}(\partial_T f_{\rm vis})\tau F^a_{\mu\nu}\tilde{F}^{\mu\nu a}\right)$$

$$\longrightarrow \quad \Gamma(\tau \to A_\mu A_\mu) = \frac{N_g}{128\pi}\frac{|\partial_T f_{\rm vis}|^2}{({\rm Re} f_{\rm vis})^2}\frac{m_\tau^3}{K_{TT}}$$

    - Moduli decay into gaugino pair

$$\mathcal{L} = -\left[\frac{1}{4\sqrt{2K_{TT}}({\rm Re} f_{\rm vis})}\left\{(\partial_T f_{\rm vis})(F^T_T + F^T_{\bar{T}}) + (\partial_T^2 f_{\rm vis})F^T\right\}\tau\lambda^a\lambda^a + {\rm h.c.}\right]$$

$$\longrightarrow \quad \Gamma(\tau \to \lambda\lambda) \simeq \frac{N_g}{128\pi}\frac{|(\partial_T f_{\rm vis})(F^T_T + F^T_{\bar{T}})|^2}{({\rm Re} f_{\rm vis})^2}\frac{m_\tau}{K_{TT}}$$

Other terms are suppressed by gaugino mass

General analysis on moduli decay

T.Higaki, KN, F.Takahashi, 1304.7987

- Coupling to MSSM sector

$$K \supset Z_u|H_u|^2 + Z_d|H_d|^2 + g(T+T^\dagger)\,(H_uH_d + \text{h.c.})$$

- Moduli decay into Higgs boson pair

$$\mathcal{L} \simeq \frac{g_T}{\sqrt{2K_{TT}Z_uZ_d}}(\partial^2\tau)(H_uH_d + \text{h.c.})$$

$$\longrightarrow \quad \Gamma(\tau \to HH) \simeq \frac{1}{8\pi}\frac{g_T^2}{K_{TT}Z_uZ_d}m_\tau^3$$

Other terms are suppressed by Higgs masses

- Moduli decay into higgsino pair

$$\mathcal{L} = -\frac{1}{\sqrt{2K_{TT}Z_uZ_d}}\left[(2g_T + gK_T)m_{3/2} + g_T(F_T^{T*} + F_{\bar{T}}^{T*}) + 2g_{TT}F^{T*}\right]\tau\tilde{H}_u\tilde{H}_d + \text{h.c.}$$

$$\longrightarrow \quad \Gamma(\tau \to \tilde{H}\tilde{H}) = \frac{1}{8\pi}\frac{|c_{\tau\tilde{h}\tilde{h}}|^2}{K_{TT}Z_uZ_d}m_\tau$$

Other terms are suppressed by higgsino mass

2013年8月24日土曜日

Moduli-MSSM matter coupling

[Conlon, Cremades, Quevedo (2006)]

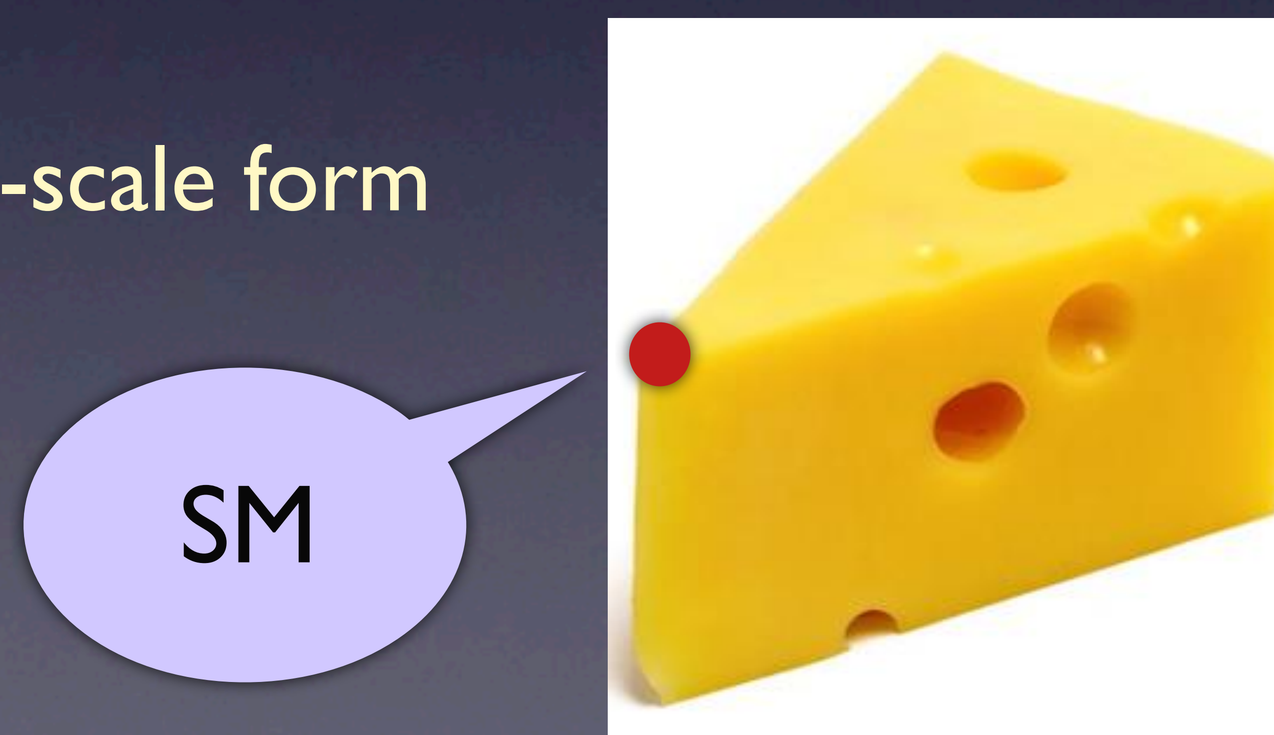
- SM on singularity
  - Kahler potential : $K_{\mathrm{MSSM}} = \dfrac{|\Phi_i|^2 + (zH_uH_d + \mathrm{h.c.})}{(T_b + T_b^\dagger)^a}$

$$\longrightarrow \quad y_{\mathrm{phys}} = \frac{e^{K/2}}{\sqrt{Z_iZ_jZ_k}}y = \frac{\tau_b^{-3/2}}{\tau_b^{-3a/2}}y$$

  - Physical Yukawa should not depend on V

$$\longrightarrow \quad \boxed{a = 1}$$

No-scale form



- Soft mass in the no-scale model

$$K = -3\ln\left[T + T^\dagger - \frac{1}{3}\{|\Phi|^2 + z(H_u H_d + \text{h.c.})\}\right]$$
$$\simeq -3\ln(T + T^\dagger) + \frac{|\Phi|^2 + z(H_u H_d + \text{h.c.})}{T + T^\dagger}$$

$G^T G_T = 3 \longrightarrow$ T dominantly breaks SUSY

$$\nabla_\phi G_\phi = \nabla_\phi G_T = 0$$

$$m_\phi^2 = e^G\left[\nabla_\phi G_k \nabla_{\bar\phi} G^k - R_{\phi\bar\phi T\bar T} G^T G^{\bar T} + K_{\phi\bar\phi}\right]$$
$$= m_{3/2}^2\left[K_{\phi\bar\phi} - 3K^{T\bar T}(K_{\phi\bar\phi T\bar T} - K^{\phi\bar\phi} K_{T\phi\bar\phi} K_{\bar T\phi\bar\phi})\right] = 0$$

- mu-term in the no-scale model

$$K \supset g(T + T^\dagger)(H_u H_d + \text{h.c.})$$

$$\mu = e^{G/2} \nabla_u G_d$$
$$= m_{3/2}[g - g_T K^{T\bar T} K_T] = 0$$

$$g = \frac{z}{T + T^\dagger}$$

- SM D7 wrapping on 4-cycle T2
  - Kahler potential : $K = \frac{(T_2 + T_2^\dagger)^\lambda \{|Q_i|^2 + z(H_u H_d + \mathrm{h.c.})\}}{\mathcal{V}^{2/3}}$

$$\longrightarrow \quad y_{\mathrm{phys}} = \frac{e^{K/2}}{\sqrt{Z_i Z_j Z_k}} y \sim \tau_2^{-3\lambda/2} y$$

  - Yukawa dependence on T2

$$S_{\mathrm{DBI}} \supset \int_{\Sigma \times 4d} \bar{\lambda} \Gamma^i (\partial_i + A_i) \lambda$$

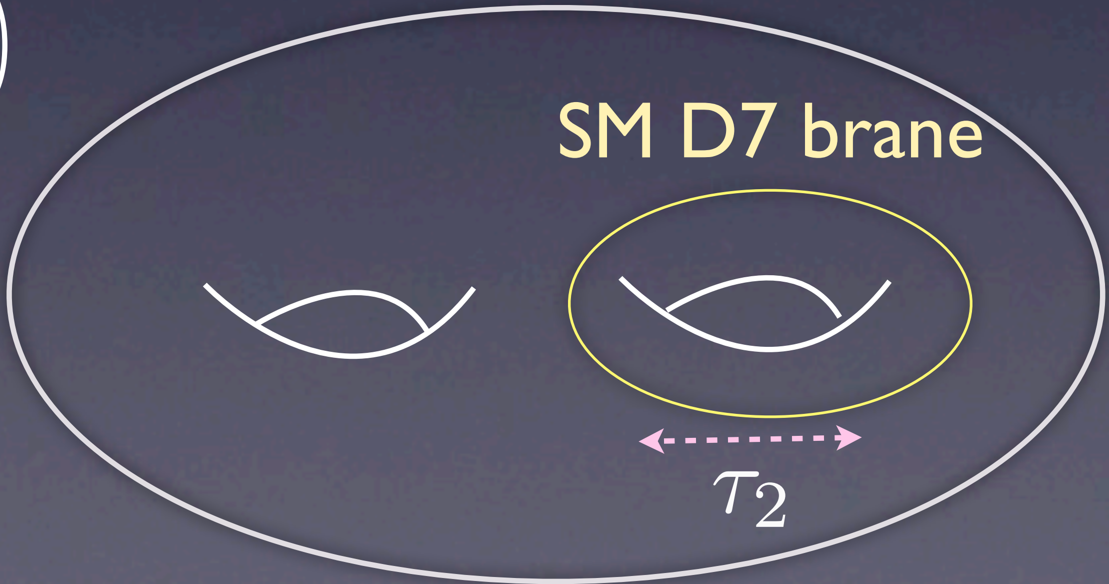
$$\longrightarrow \quad S_{4\mathrm{d}} \sim \left(\int_\Sigma \psi_6^\dagger \psi_6 \right) \int d^4x \bar{\psi}_4 \gamma^\mu \partial_\mu \psi_4 + \left(\int_\Sigma \psi_6^\dagger \phi_6 \psi_6 \right) \int d^4x \phi_4 \bar{\psi}_4 \psi_4$$

= 1   = y_phys

$$\psi_6 \to \frac{\psi_6}{\sqrt{\beta}} \quad \text{for} \quad \tau_2 \to \beta \tau_2 \qquad \left(\int_\Sigma = \tau_2 \right)$$

$$y_{\mathrm{phys}} \to \frac{y_{\mathrm{phys}}}{\sqrt{\beta}} \quad \text{for} \quad \tau_2 \to \beta \tau_2$$

$$\longrightarrow \quad \boxed{\lambda = \frac{1}{3}}$$



Moduli-MSSM Gauge coupling

- DBI action

gauge field on Dp brane

$$S_{\rm DBI} = -\mu_p \int_{p+1} d^{p+1}x e^{-\phi}\sqrt{-\det\left(G + B - 2\pi\alpha' F\right)}$$

Dp brane worldvolume

Dp brane tension

$$\supset \frac{\alpha'^{-(p-3)/2}}{4g_s(2\pi)^{p-2}}\int d^{p+1}x\sqrt{-g}\,{\rm tr}\,F_{\mu\nu}F^{\mu\nu} \qquad \mu_p = \frac{\alpha'^{-(p+1)/2}}{(2\pi)^p}$$

4d gauge coupling : $\frac{1}{g_{\rm YM}^2} = \frac{\alpha'^{(3-p)/2}}{g_s(2\pi)^{p-2}}V_{p-3}$ Kahler moduli

- Chern-Simons action : Dp-brane $\longleftrightarrow$ R-R fields

$$S_{\rm CS} = \mu_p \int_{p+1} C_q \wedge e^{2\pi\alpha' F - B_2}$$

axion

$$\supset \mu_p \int_{p+1} C_{p+1} + 2\pi\alpha' \int_{p+1} C_{p-1}\wedge {\rm tr}F + 2\pi^2\alpha'^2 \int_{p+1} C_{p-3}\wedge {\rm tr}F^2$$

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