

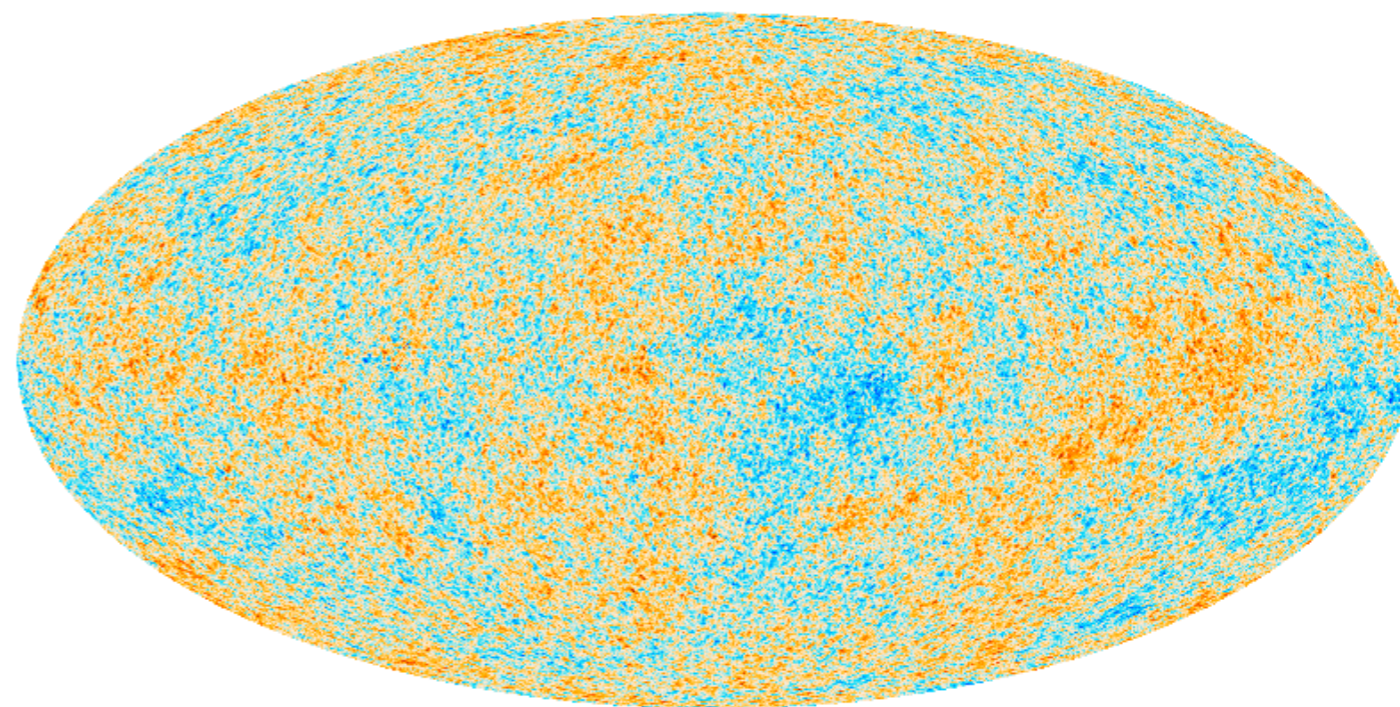
# Axionic dark radiation from string moduli

Kazunori Nakayama (University of Tokyo)

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

PASCOS2013 @ Taiwan (2013/11/20)





# What we have shown :

- Kahler moduli :  $T_j = \tau_j + i a_j$   
moduli axion
- Moduli decays into very light axion :

$$\tau_j \rightarrow 2a_j$$

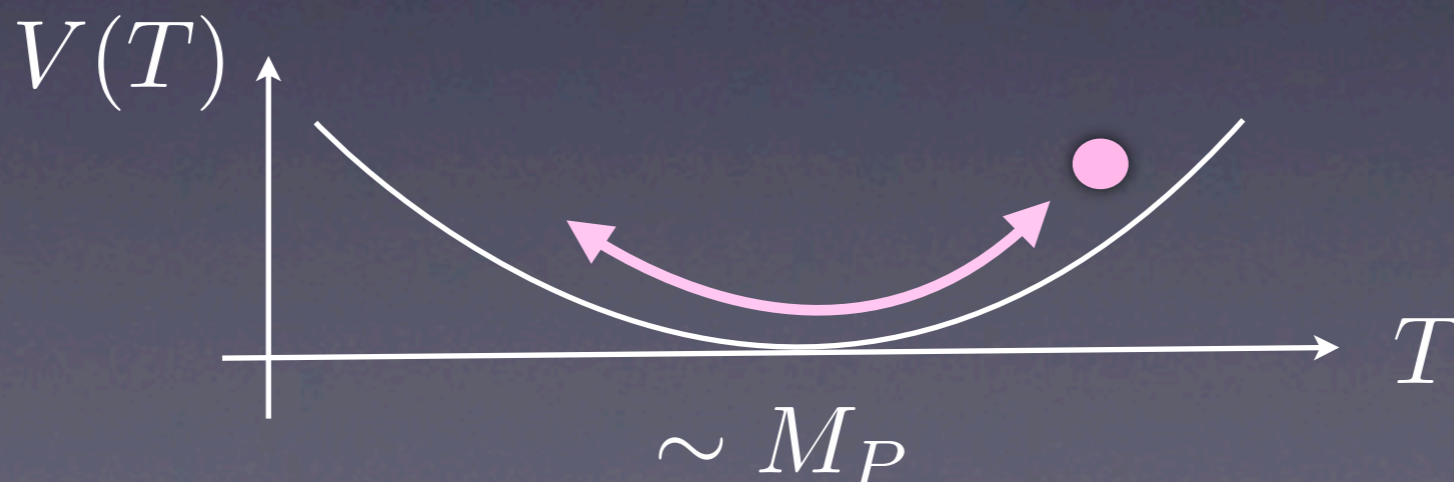
- Too much axionic dark radiation  
in light of PLANCK

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



# Moduli Problem

- Moduli abundance

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

$T_R$  : reheat temperature

$z_i$  : moduli initial amplitude

- Moduli lifetime

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

- Big bang nucleosynthesis constraint

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

[ Kawasaki, Kohri, Moroi (2004) ]

# Moduli Problem

- Moduli abundance

$$\frac{\rho_T}{s} = \frac{1}{8} T_R \left( \frac{z_i}{M_P} \right)^2 \sim 10^5 \text{ GeV} \left( \frac{T_R}{10^{26} \text{ GeV}} \left( \frac{z_i}{M_P} \right)^2 \right)$$

- Moduli lifetime:  $\tau \sim 10^4 \text{ sec} \left( \frac{1 \text{ TeV}}{m_T} \right)^3$  : moduli initial amplitude

**Moduli problem**

- Big bang nucleosynthesis constraint

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

[ Kawasaki, Kohri, Moroi (2004) ]



# Heavy moduli ?

- Moduli decay before BBN ( $m_T \gg \mathcal{O}(10) \text{ TeV}$ )
  - *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  
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# Moduli-induced axion problem

T.Higaki, KN, F.Takahashi, I 304.7987

# Moduli in type II B string

- Kahler moduli :  $T$   
Shift symmetry :  $T \rightarrow T + i\alpha$   
cf) 10d gauge symmetry  $C_4 \rightarrow C_4 + d\Lambda$



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

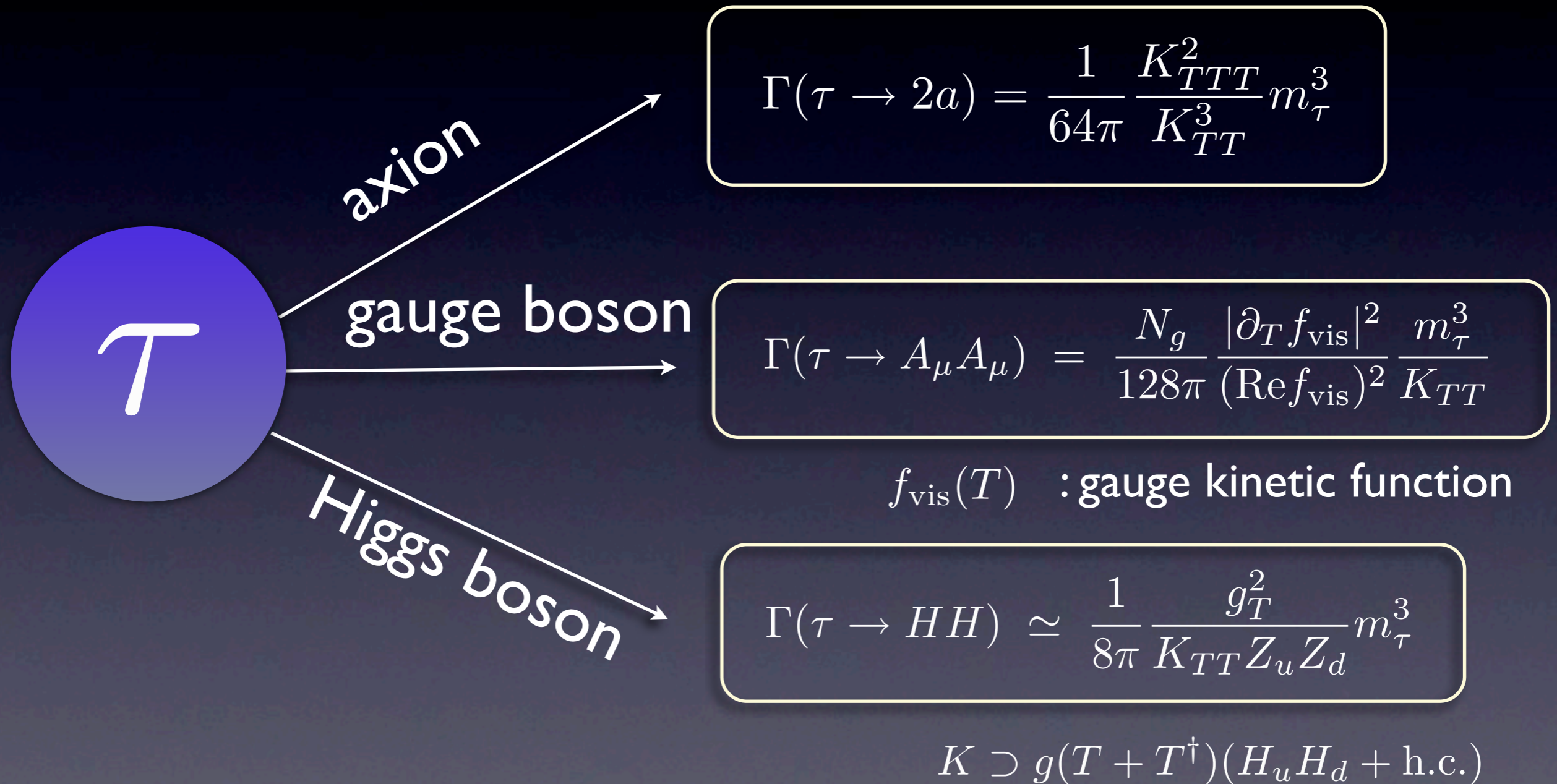
$$T - \langle T \rangle \equiv \frac{\tau + ia}{\sqrt{2K_{TT}}}$$

axion

- Suppose that moduli stabilization does not give axion mass

# General analysis on moduli decay

T.Higaki, KN, F.Takahashi, I304.7987



Note : decay into their superpartners can also be sizable

# General analysis on moduli decay

T.Higaki, KN, F.Takahashi, I304.7987

axion

Branching ratio  
into axion ( $B_a$ ) is  
generally  $\mathcal{O}(1)$

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

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

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

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

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

Note : decay into their superpartners can also be sizable



# Planck constraint on $N_{\text{eff}}$

- Radiation energy density  $\rho_{\text{rad}} = \left[ 1 + \frac{7}{8} N_{\text{eff}} \left( \frac{4}{11} \right)^{4/3} \right] \rho_{\gamma}$

- CMB constraint:

$$N_{\text{eff}} = 3.36^{+0.68}_{-0.64} @ 95\% \text{CL}$$

Planck+WMAP pol+ high l

[Ade et al. 1303.5076]



- Axion dark radiation abundance:

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



$$B_a \lesssim 0.2$$

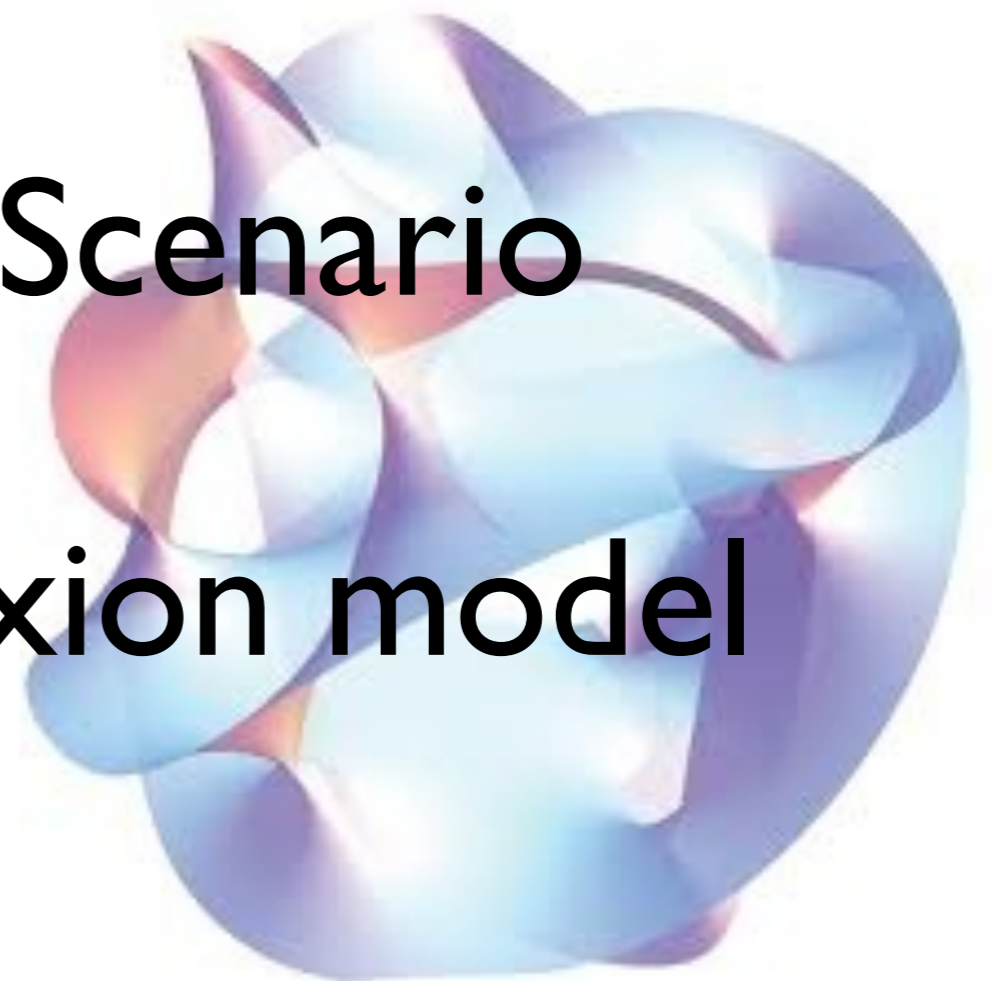
→ Constraint on moduli stabilization model



**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:  $\mathcal{V} = \mathcal{V}_0 - \mathcal{V}_{\text{hole}}$

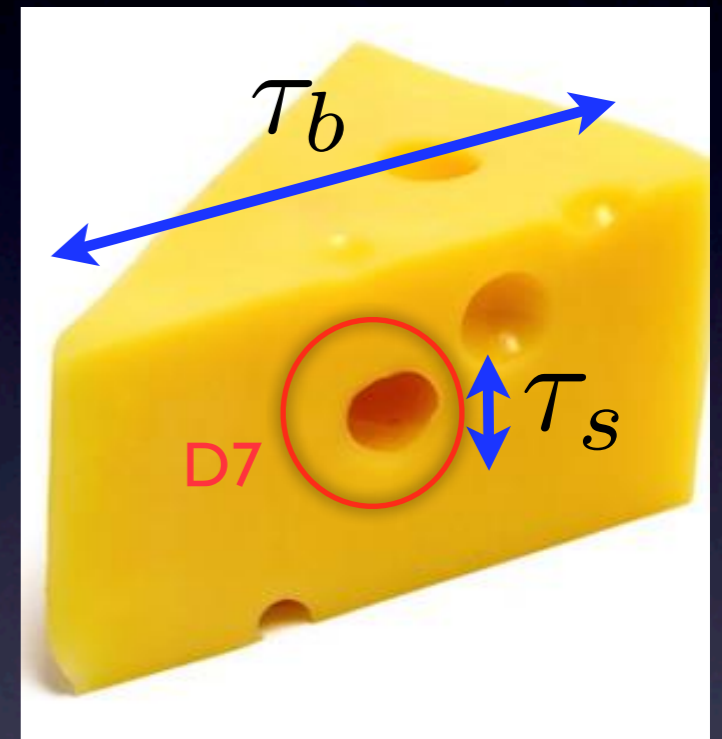
The simplest :  $\mathcal{V}_0 = (T_b + T_b^\dagger)^{3/2}$

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

- Kahler and Superpotential

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

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



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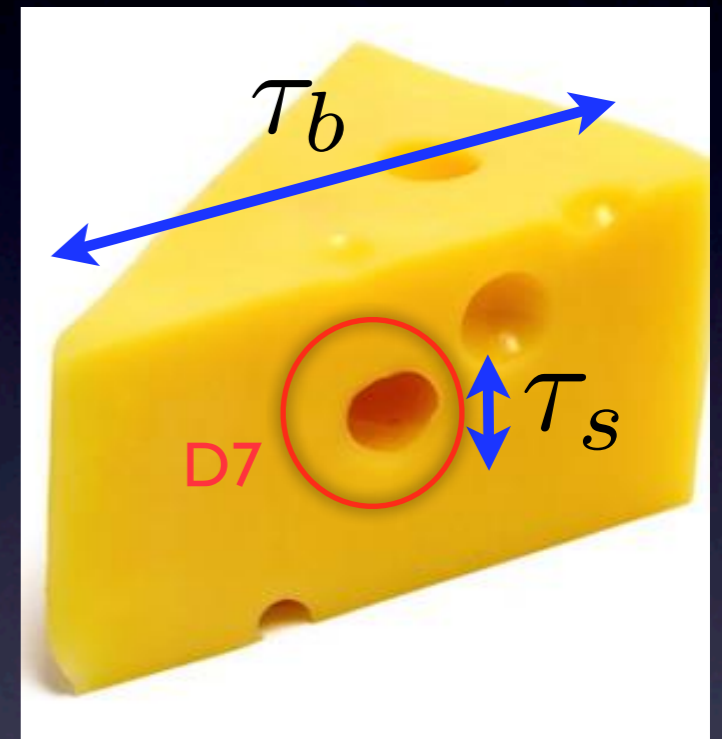
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Stabilized a la KKLT

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



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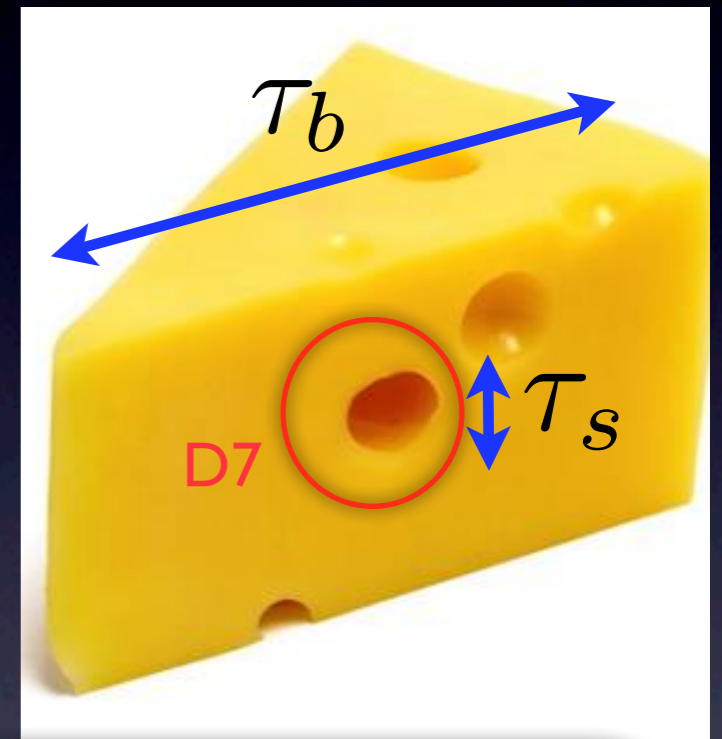
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Stabilized a la KKLT

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

Stabilized by alpha' correction.

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



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

  
 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)

- Kahler and Superpotential

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

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

Stabilized a la KKLT

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

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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  $m_{\tau_s} \sim m_{a_s} \sim \frac{1}{\mathcal{V}}$

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

$$m_{a_b} = 0 \quad \text{: Axion}$$

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

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

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

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

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

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

→ **Branching ratio into axion:**

$$B_a = \frac{1}{1 + 2z^2}$$

**Independent of moduli mass**



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

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) ]

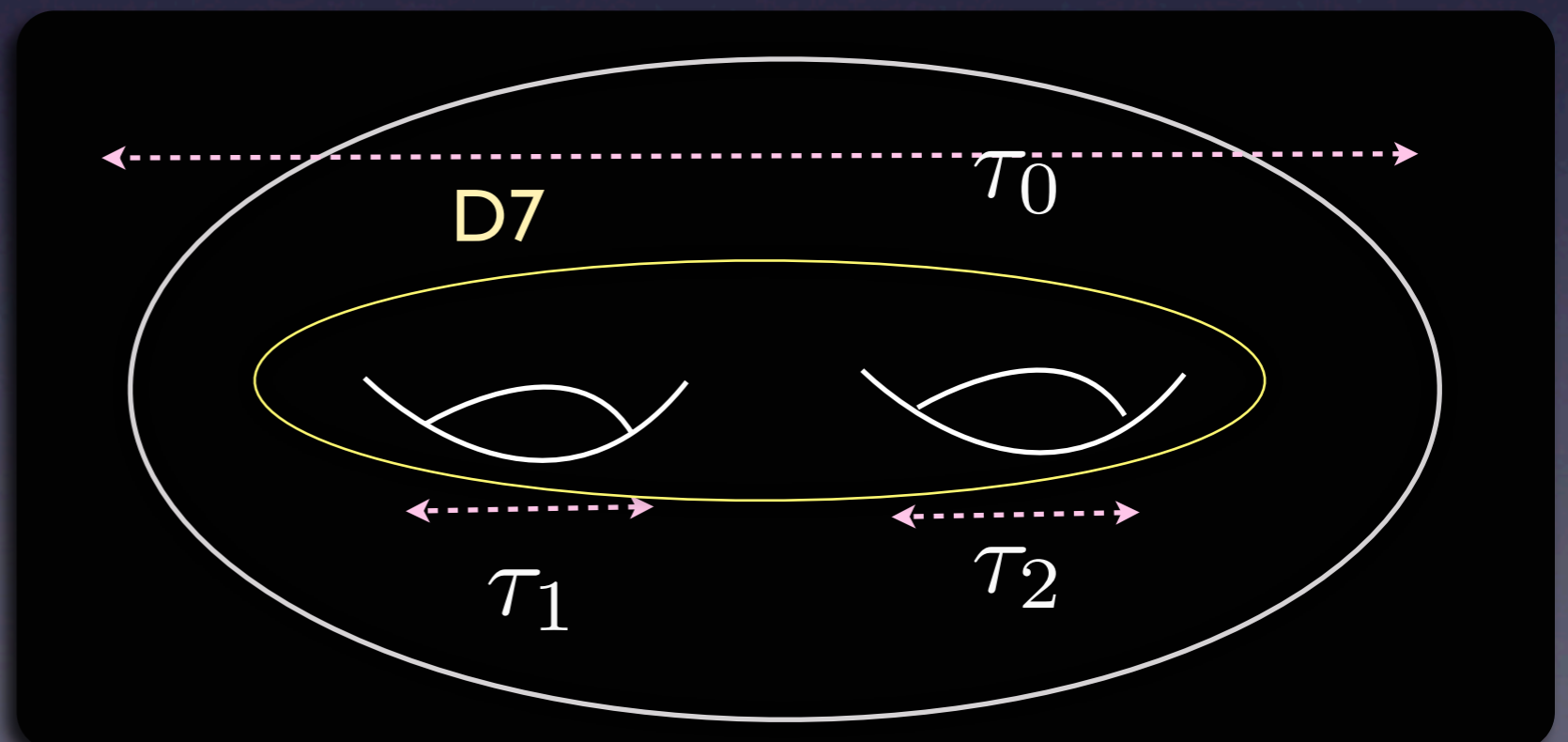
- String theoretic QCD axion model

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

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

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

$$W = A e^{-\alpha T_0} + B e^{-\beta(T_1 + n T_2)} + W_0$$



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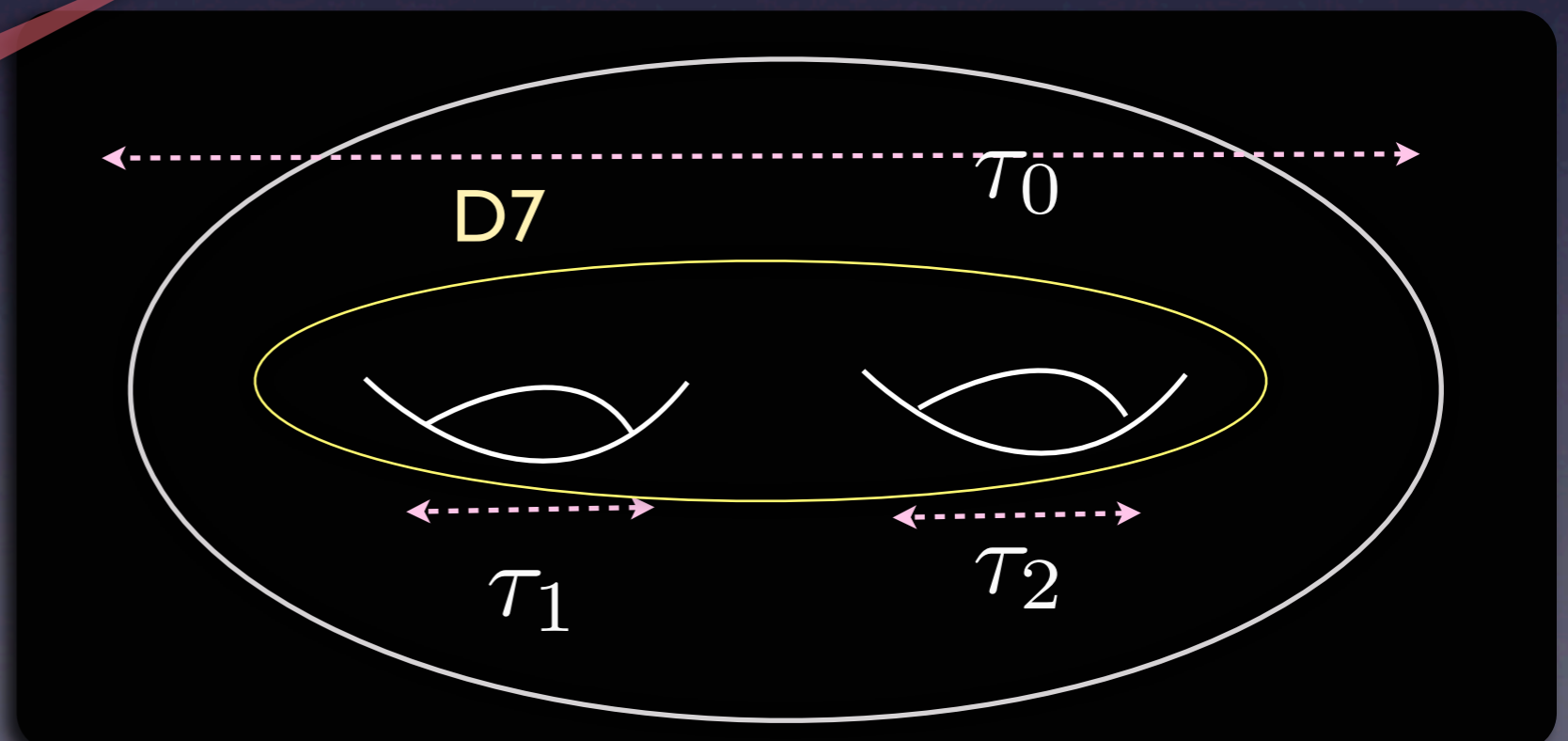
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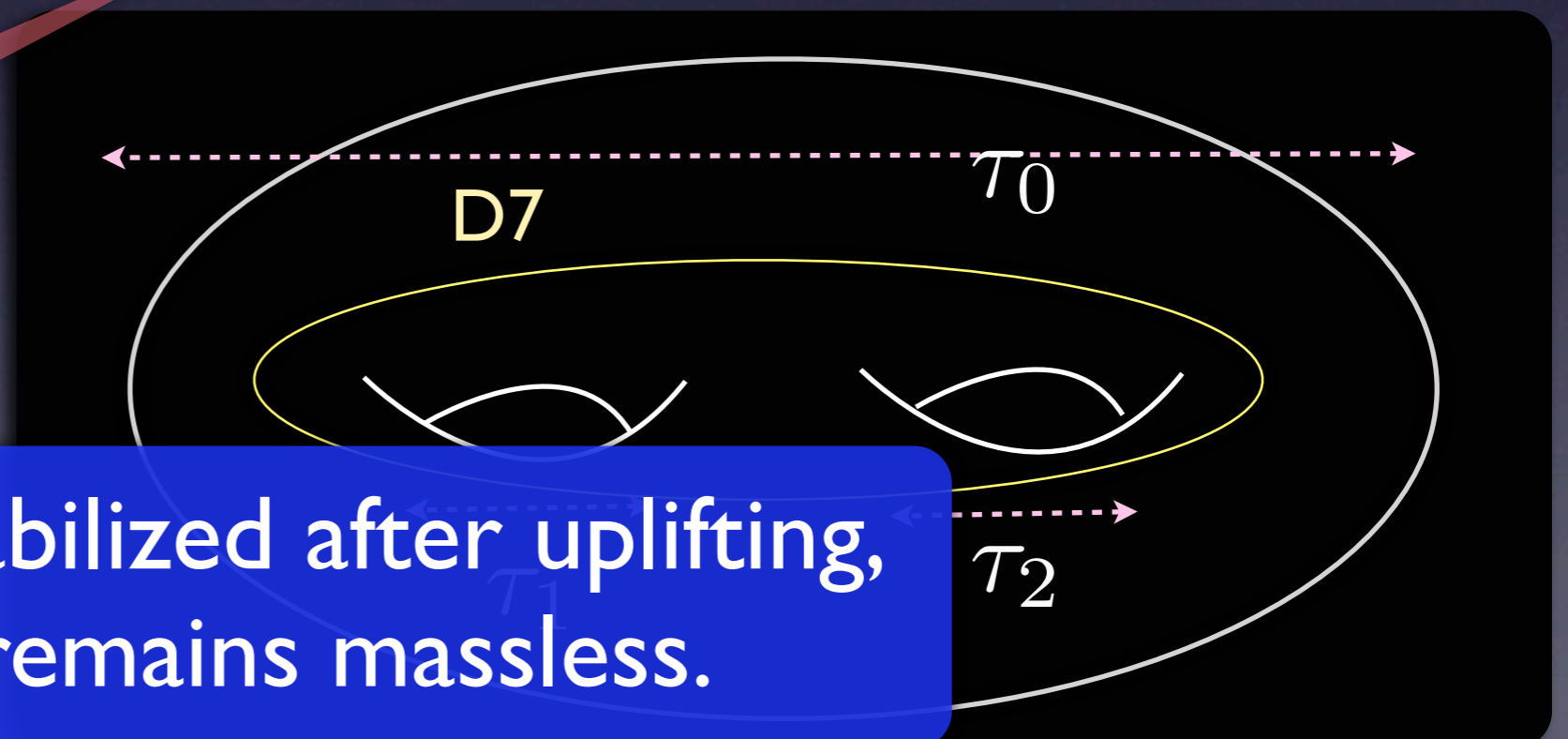
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$$W = A e^{-\alpha T_0} + B e^{-\beta (T_1 + n T_2)} + W_0$$

Stabilized a la  
KKLT



$A \equiv n T_1 - T_2$  is stabilized after uplifting,  
while  $\text{Im} \mathcal{A} \equiv a$  remains massless.

- SM brane wraps cycle T2

SM gauge kinetic function :  $f_{\text{vis}} = \frac{T_2}{4\pi}$

$$A \equiv nT_1 - T_2 \equiv s + ia$$

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



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**QCD axion to solve strong CP problem**



SM D7 brane

- SM brane wraps cycle T2

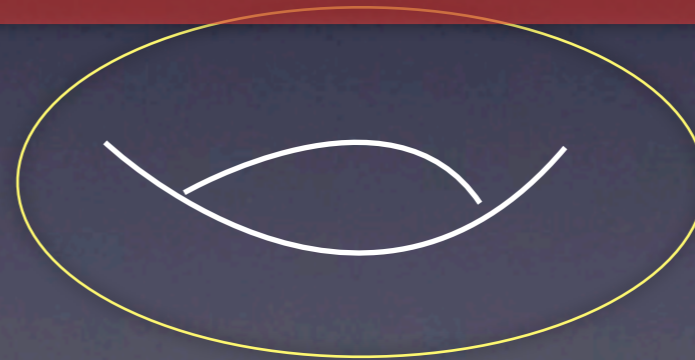
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Lightest moduli  
(saxion)

**QCD axion to  
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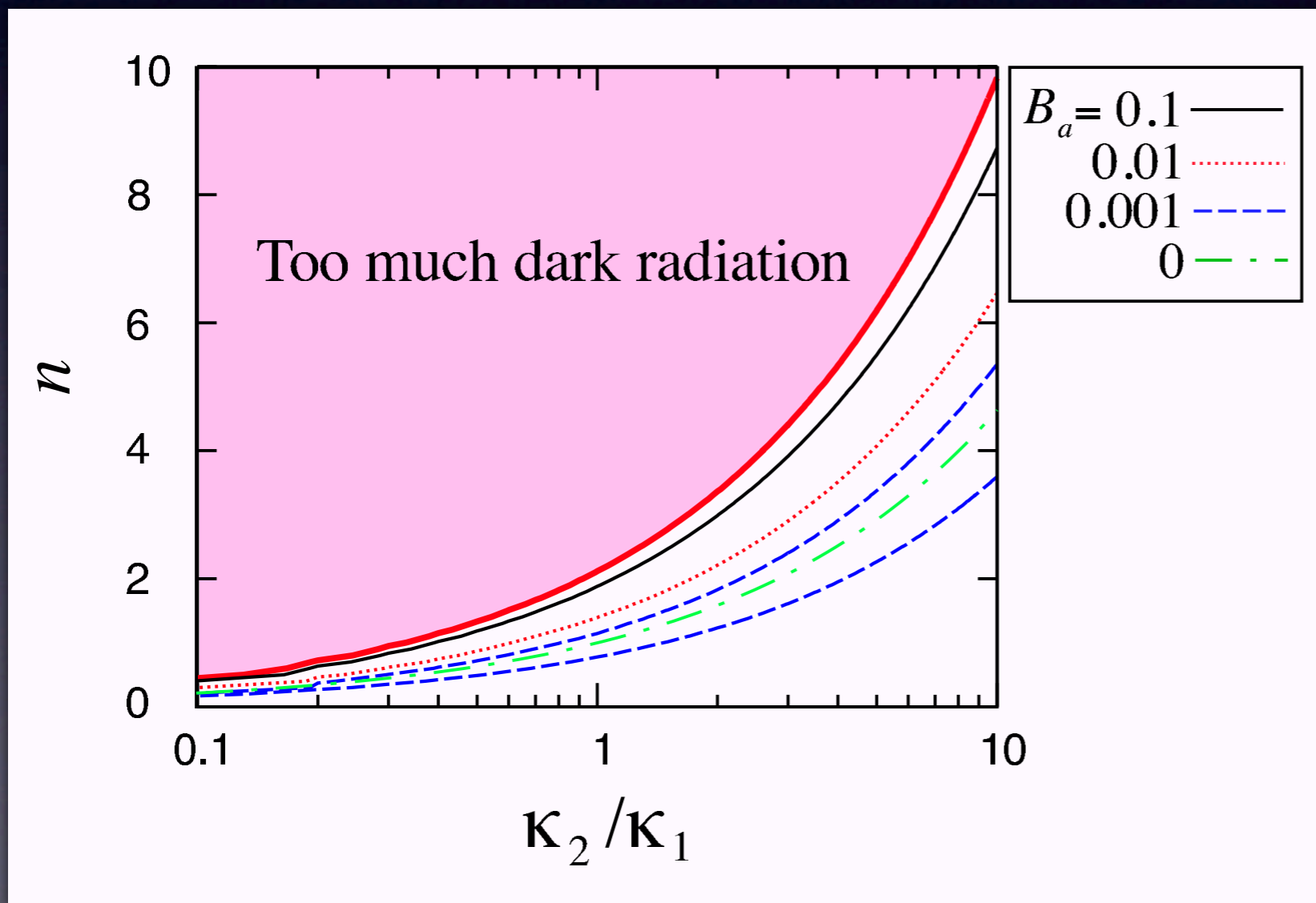
SM D7 brane

• Moduli (Saxion) decay rate

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

• Two axion :  $\Gamma_a \simeq \frac{(n^2 \kappa_1^2 - \kappa_2^2)^2}{768 \pi \kappa_2^3} \frac{M_s^3}{M_P^2}$   $m_s \sim \mathcal{O}(10^3) \text{ TeV}$

• 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.

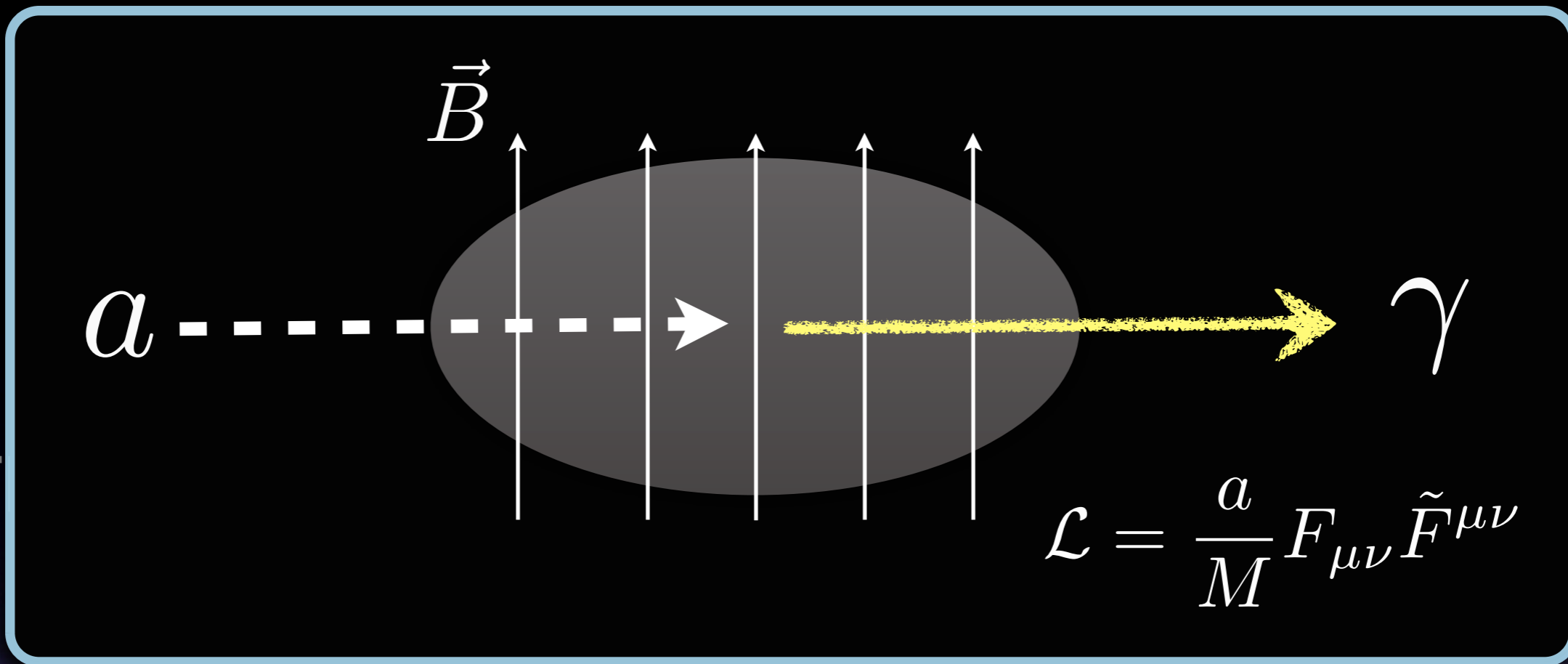
[ T.Higaki, KN, F.Takahashi, 1304.7987 ]



# Detecting/constraining axionic dark radiation

- The presence of axionic dark radiation seems to be ubiquitous in string theory  $\Delta N_{\text{eff}} \gtrsim \mathcal{O}(0.1)$
- Can we probe it?
  - Axion conversion into X-ray photon in galaxy cluster  
[ J.Conlon, M.C.D.Marsh, I 305.3603 ]
  - Axion-photon conversion in the early Universe under primordial magnetic field [ T.Higaki, KN, F.Takahashi, I 306.6518 ]
  - Any other idea?

• T



0.1)

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• Any other idea?

# Summary

- Light axions often appear after moduli stabilization
- Moduli branch into axion is generically  $\mathcal{O}(1)$   
 $\longleftrightarrow$  Planck constraint :  $B_a \lesssim 0.2$
- The branch does not depend on moduli mass  
The problem exists even for heavy moduli  
( $m_T \gg \mathcal{O}(10) \text{ TeV}$ )

**“Moduli-induced axion problem”**

# 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) ]

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

→ Suppression is not exponential but power in  $c$   
High inflation scale & low reheat temp. is needed.

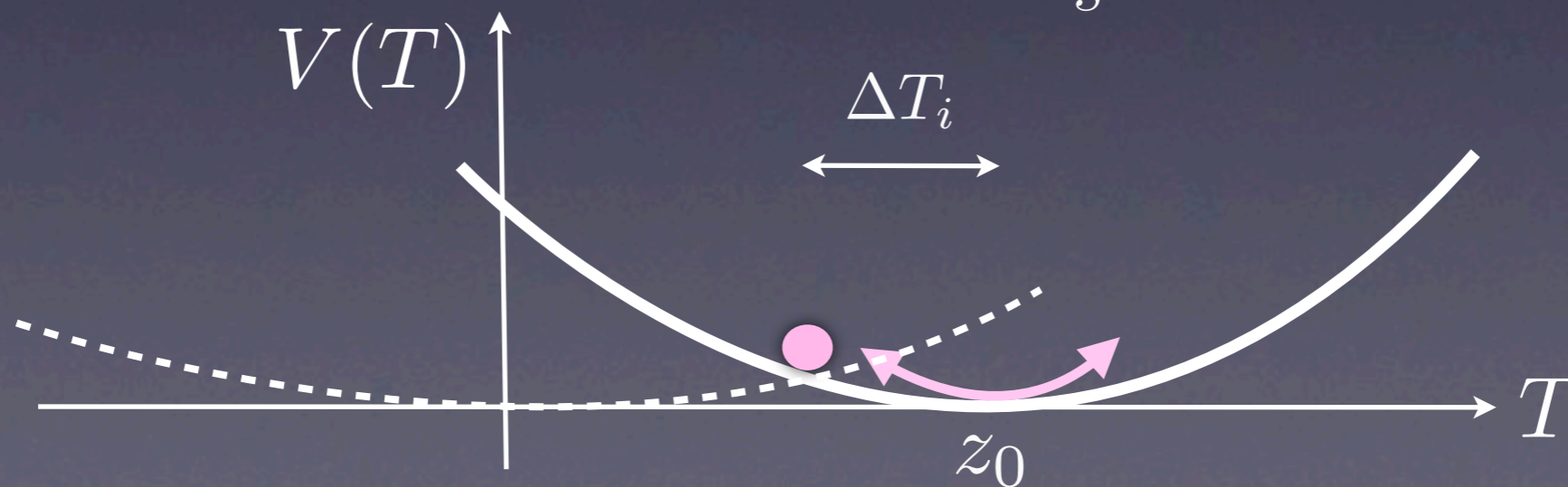
[ KN, F.Takahashi, T.Yanagida (2011) ]

# 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, I 09.2073 ]

- $H_{\text{inf}} \gg m_T$  :  $\Delta T_i \sim z_0 \rightarrow \frac{\rho_T}{s} \sim \frac{1}{8} T_R \left( \frac{z_0}{M_P} \right)^2$
  - $H_{\text{inf}} \ll m_T$  :  $\Delta T_i \sim \frac{H_{\text{inf}}^2}{m_T^2} z_0 \rightarrow \frac{\rho_T}{s} \sim \frac{1}{8} T_R \left( \frac{z_0}{M_P} \right)^2 \left( \frac{H_{\text{inf}}}{m_T} \right)^2$   
 [ cf. Kallosh-Linde bound ]
- $(m_{\text{inf}} \gg m_T)$   
 $(m_{\text{inf}} \ll m_T)$
- $\frac{\rho_T}{s} \sim 0$



# General analysis on moduli decay

T.Higaki, KN, F.Takahashi, I 304.7987

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

$$\mathcal{L} = \frac{K_{TTT}}{\sqrt{2}K_{TT}^{3/2}} \tau (\partial a)^2 \longrightarrow$$

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

- Moduli decay into axino pair (if kinematically allowed)

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

$\longrightarrow$

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

# General analysis on moduli decay

T.Higaki, KN, F.Takahashi, I 304.7987

- Coupling to MSSM sector

- Gauge kinetic function  $f_{\text{vis}}(T)$

- Moduli decay into gauge boson pair

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

→

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

- Moduli decay into gaugino pair

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

→

$$\Gamma(\tau \rightarrow \lambda\lambda) \simeq \frac{N_g}{128\pi} \frac{|(\partial_T f_{\text{vis}})(F_T^T + F_{\bar{T}}^T)|^2}{(\text{Re}f_{\text{vis}})^2} \frac{m_\tau}{K_{TT}}$$

Other terms are suppressed by gaugino mass



# General analysis on moduli decay

T.Higaki, KN, F.Takahashi, I 304.7987

- Coupling to MSSM sector

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

- Moduli decay into Higgs boson pair

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

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

Other terms are suppressed by Higgs masses

- Moduli decay into higgsino pair

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

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

Other terms are suppressed by higgsino mass

# Moduli-MSSM matter coupling

[ Conlon, Cremades, Quevedo (2006) ]

- SM on singularity

- Kahler potential : 
$$K_{\text{MSSM}} = \frac{|\Phi_i|^2 + (zH_uH_d + \text{h.c.})}{(T_b + T_b^\dagger)^a}$$

$$\longrightarrow y_{\text{phys}} = \frac{e^{K/2}}{\sqrt{Z_i Z_j Z_k}} y = \frac{\tau_b^{-3/2}}{\tau_b^{-3a/2}} y$$

- Physical Yukawa should not depend on V

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

No-scale form

SM



- Soft mass in the no-scale model

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

$$\simeq -3 \ln(T + T^\dagger) + \frac{|\Phi|^2 + z(H_u H_d + \text{h.c.})}{T + T^\dagger}$$

$$G^T G_T = 3 \quad \longrightarrow \quad \mathbf{T \text{ dominantly breaks SUSY}}$$

$$m_\phi^2 = e^G \left[ \nabla_\phi G_k \nabla_{\bar{\phi}} G^{\bar{k}} - R_{\phi\bar{\phi}T\bar{T}} G^T G^{\bar{T}} + K_{\phi\bar{\phi}} \right] \quad \nabla_\phi G_\phi = \nabla_\phi G_T = 0$$

$$= m_{3/2}^2 \left[ K_{\phi\bar{\phi}} - 3K^{T\bar{T}} (K_{\phi\bar{\phi}T\bar{T}} - K^{\phi\bar{\phi}} K_{T\phi\bar{\phi}} K_{\bar{T}\phi\bar{\phi}}) \right] = 0$$

- mu-term in the no-scale model

$$\mu = e^{G/2} \nabla_u G_d \quad K \supset g(T + T^\dagger)(H_u H_d + \text{h.c.})$$

$$= m_{3/2} [g - g_T K^{T\bar{T}} K_T] = 0 \quad g = \frac{z}{T + T^\dagger}$$

- SM D7 wrapping on 4-cycle T2

- Kahler potential :  $K = \frac{(T_2 + T_2^\dagger)^\lambda \{|Q_i|^2 + z(H_u H_d + \text{h.c.})\}}{\nu^{2/3}}$

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

- Yukawa dependence on T2

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

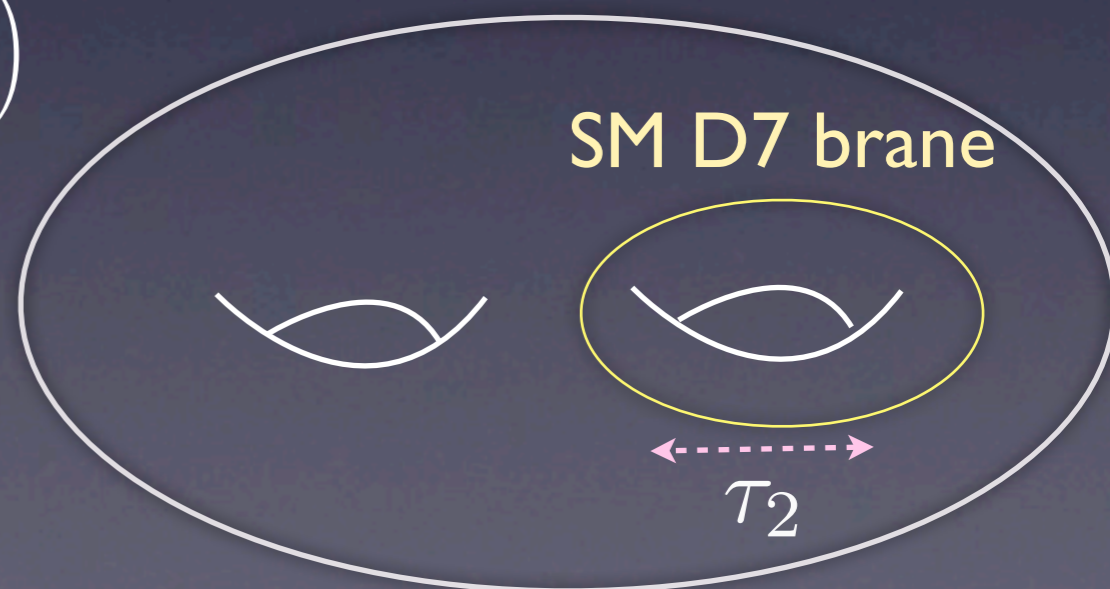
$$\longrightarrow S_{4d} \sim \left( \int_{\Sigma} \psi_6^\dagger \psi_6 \right) \int d^4x \bar{\psi}_4 \gamma^\mu \partial_\mu \psi_4 + \left( \int_{\Sigma} \psi_6^\dagger \phi_6 \psi_6 \right) \int d^4x \phi_4 \bar{\psi}_4 \psi_4$$

$= |$ 
 $= y_{\text{phys}}$

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

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

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



# Moduli-MSSM Gauge coupling

- DBI action

gauge field on Dp brane

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

Dp brane worldvolume

Dp brane tension

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

$$\mu_p = \frac{\alpha'^{-(p+1)/2}}{(2\pi)^p}$$

4d gauge coupling :

$$\frac{1}{g_{\text{YM}}^2} = \frac{\alpha'^{(3-p)/2}}{g_s(2\pi)^{p-2}} V_{p-3}$$

Kahler moduli

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

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

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

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

axion