2013 Oct.24th@Tohoku

Particle Physics and Cosmology after the discovery of Higgs boson

Tohoku Forum for Creativity

Moduli-Induced Axion Problem

Tetsutaro Higaki

(KEK)

1208.3563 and 1304.7987

with **K. Nakayama** and **F. Takahashi**

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Moduli-Induced Axion Probe for extra dimensions

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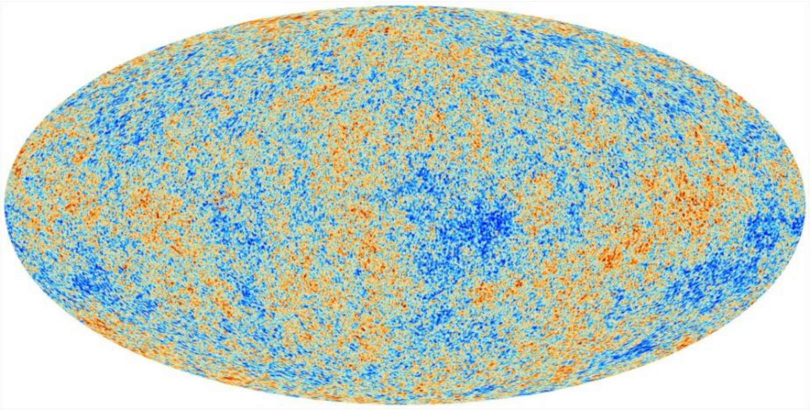
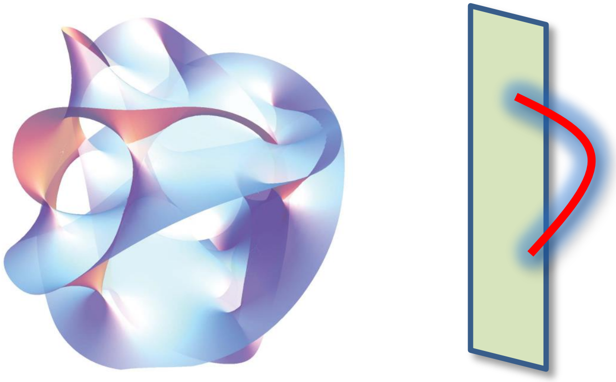
Cosmological test for string models



CMB



Ex-dim. + D-branes

Axionic dark radiation (= relativistic DM):

$$\Delta N_{\mathrm{eff}} = O(0.1)$$

Key: Moduli problem in reheating

$$\Phi \rightarrow aa$$

Φ: Moduli/Inflaton   a: Axion

Axionic dark radiation exists

even for m_Φ >> 100TeV.

Dark radiation

Dark radiation ΔN_{eff} in ρ_{rad}

$$\rho_{\mathrm{rad}} = \left[1 + \frac{7}{8} N_{\mathrm{eff}} \left(\frac{4}{11}\right)^{4/3}\right] \frac{\pi^2}{15} T_\gamma^4$$

$$\boxed{N_{\mathrm{eff}} = \Delta N_{\mathrm{eff}} + 3.046}$$

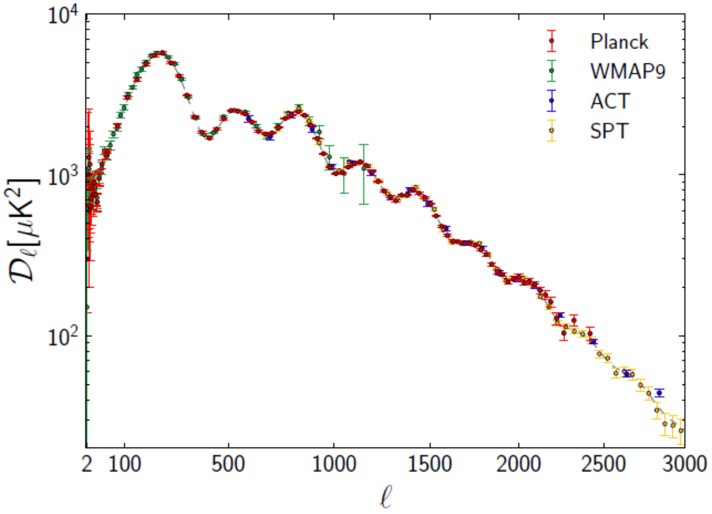
ΔN_{eff}: Dark radiation, N_{eff}: Effective neutrino number,
3.046: The SM value

Effective neutrino number N_{eff}

- Observations from Planck (95%): **[Planck collaborations]**

$$N_{\text{eff}} = 3.36^{+0.68}_{-0.64}, \quad 3.30^{+0.54}_{-0.51}, \quad 3.62^{+0.50}_{-0.48}$$

(CMB) (CMB+BAO) (CMB+H_0)



Effective neutrino number N_{eff}

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(CMB) (CMB+BAO) (CMB+H_0)

Dark radiation is hinted, while tension between H_0 measurement and CMB/BAO.

See also **[Hamann and Hasenkamp]:** $N_{\mathrm{eff}} = 3.66 \pm 0.30\ (1\sigma)$

(CMB+HST+C+BAO+WL)

Axions in string theory:
Dark radiation candidates

QCD axion: Strong CP and CDM

$$\mathcal{L} \supset \frac{a}{32\pi^2 f_a}\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\nu\rho}$$

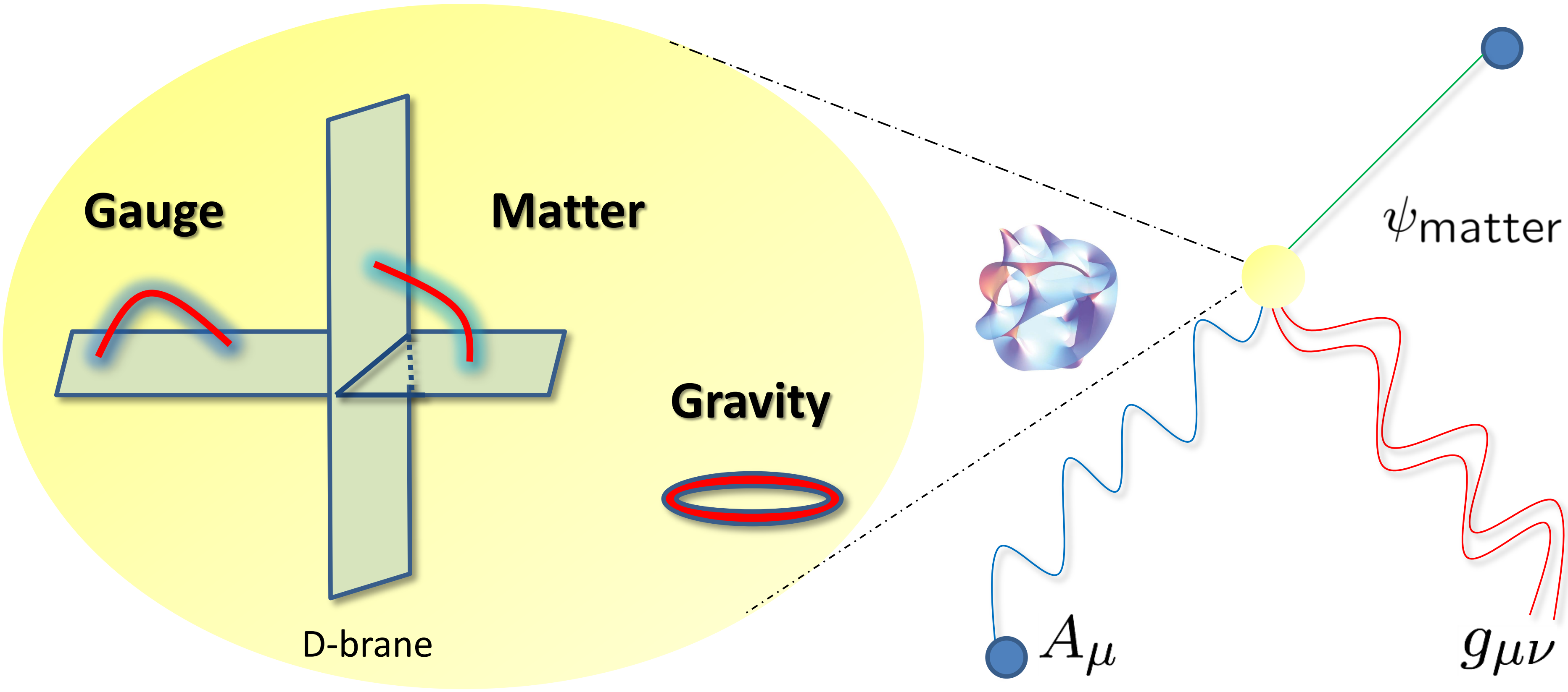
Ultralight $\sim 10^{-6}$ eV for $\underline{f_a = 10^{12}\ \text{GeV}}$.

Original motivations:

- A solution of strong CP problem: $\theta < 10^{-10}$
- A candidate of CDM

Motivation for string theory

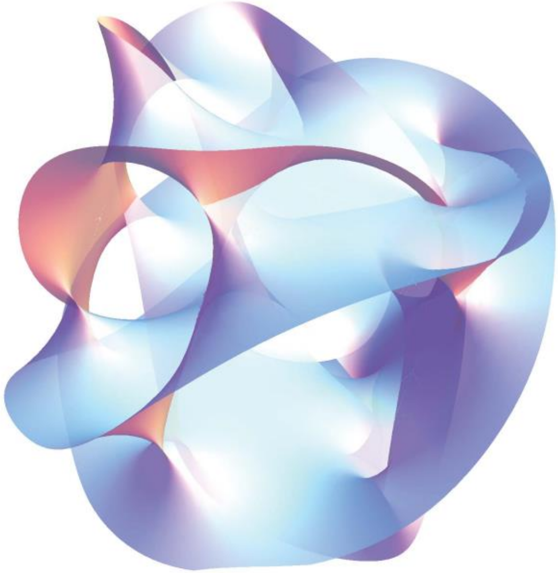
Unified theory including quantum gravity!



Axions in string theory

- Axions via compactifications:

$$a^i = \int_{\Sigma_n^i} C_n$$



C_n: n-form gauge field for strings/branes.

They **can be ultralight** and **very weak**

- – shift symmetry: $a \to a + \delta$;
- – solution of CP and/or CDM with $f_a \sim M_{\text{string}}$ or M_{P}.

Moduli

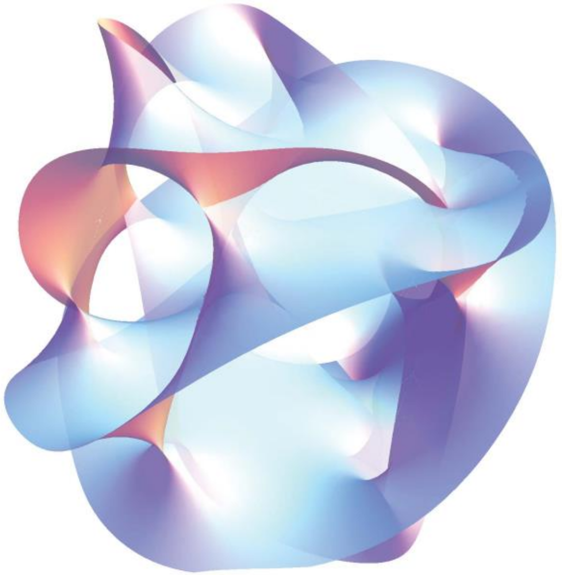
Reheating field:

- **String moduli**:

$$\Phi^i = \mathrm{Vol}(\Sigma_n^i)$$

Long lifetime: Light + 1/M_{Pl}

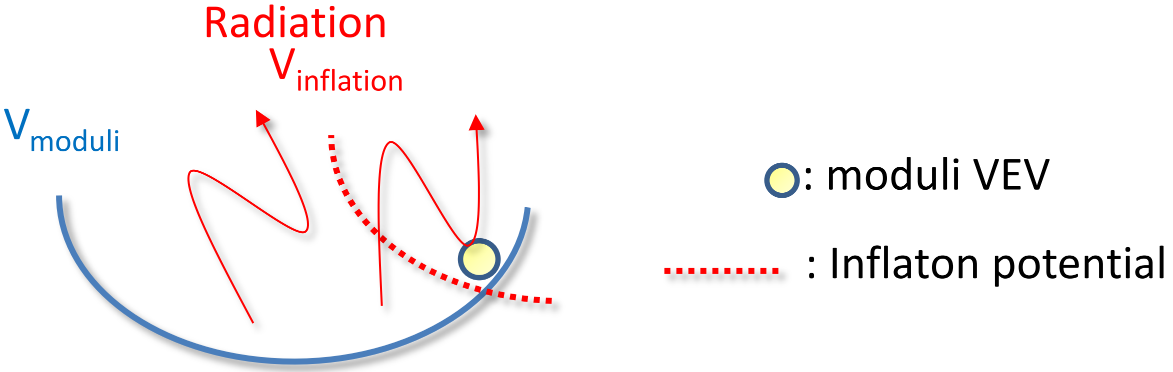
(if SUSY)



- Other possibilities:
  - – Inflaton (also in non-SUSY if coupled to axions)
  - – Open string state, e.g., SUSY-breaking fields

[Coughlan et al.]

Moduli oscillation



The decay = Reheating + dark radiation.

$$\Phi \to a$$

$$\Phi \to A_\mu, \;\; H, \cdots$$

Moduli problems

- Non-SUSY moduli: $m_{\Phi} \leqq m_{3/2}$ + light axion

  Moduli-Induced Axion problem:

  [Cicoli, Conlon, Quevedo],
  [TH, Takahashi],
  [TH, Nakayama, Takahashi].

$$\Delta N_{\text{eff}} \gg 0.1 : \quad \Phi \to a.$$

- SUSY moduli: $m_{\Phi} > m_{3/2}$

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

  Moduli-induced gravitino problem:

$$\Omega_{DM} \gg 0.1 : \quad \Phi \to \psi_{3/2} \to \chi_{\text{DM}}$$

Moduli-Induced Axion Problem; moduli decay modes

We will use 4D N=1 SUGRA.

($M_{Pl} = 1$)

Axion production via the kinetic term

$$\mathcal{L}_{\mathrm{kin.}} = K_{T\bar{T}}(\partial_\mu a)^2; \qquad K_T = \partial_T K$$

$$\Longrightarrow \quad \langle K_{TT\bar{T}} \rangle \Phi (\partial_\mu a)^2 + \cdots .$$

Moduli-axions coupling exists in general!

Φ: Moduli; K: invariant under δT = iα:

$$T = \Phi + ia; \qquad K = K(T + T^\dagger)$$

The decay fractions of Φ

$$\Gamma_a \equiv \Gamma(\Phi \to aa) = \frac{m_\Phi^3}{64\pi}\frac{K_{TT\bar{T}}^2}{K_{T\bar{T}}^3}$$

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$$K \supset Z_{\text{GM}} H_u H_d$$

$$W \supset f_{\text{vis}} \mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\Gamma(\Phi \to HH) \simeq \frac{m_\Phi^3}{8\pi} \frac{(\partial_T Z_{\text{GM}})}{Z_{H_u} Z_{H_d}},$$

$$\Gamma(\Phi \to A_\mu A_\mu) \simeq N_g \frac{m_\Phi^3}{128\pi} \frac{|\partial_T f_{\text{vis}}|^2}{\text{Re}(f_{\text{vis}})^2 K_{T\bar{T}}}.$$

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$$\Gamma_a \sim \Gamma(\Phi \to \text{radiation}) \sim \frac{m_\Phi^3}{4\pi}.$$

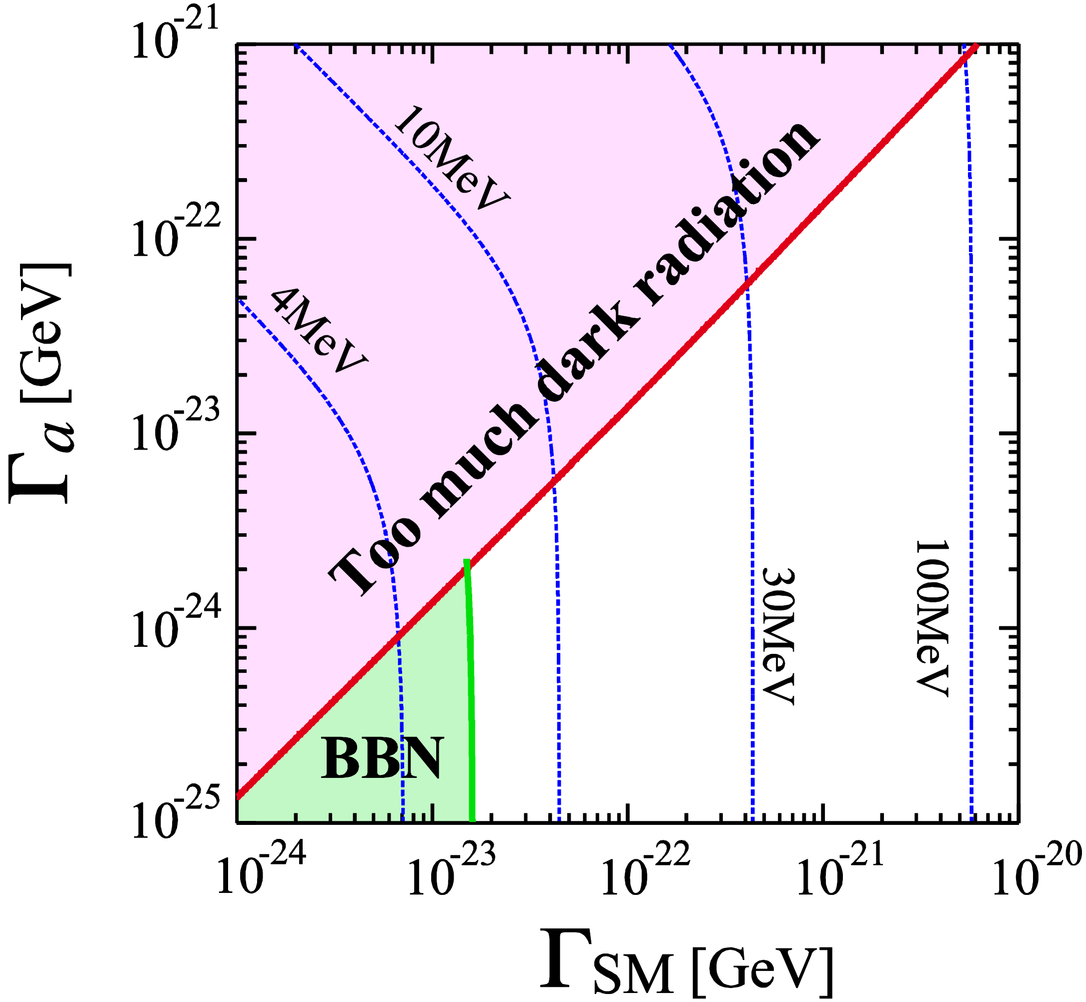
$$\Longrightarrow \quad \Delta N_{\text{eff}} = \mathcal{O}(1)!$$

$\because \; \rho_a \sim \rho_{\text{radiation}} \sim \rho_\nu$ after moduli decay

Constraint on decay widths of Φ

[TH, Nakayama, Takahashi]

$$T_R = (1-B_a)^{\frac{1}{4}} \left(\frac{\pi^2 g_*}{90}\right)^{-\frac{1}{4}} \sqrt{\Gamma_{\rm total} M_P}$$



ΔN_{eff} >0.84 ruled out:

Br(Φ→2a) > O(0.1)

or

T_R < O(1) MeV

Two examples:
The problem and solution

1. No-scale a la Large Volume Scenario

[Balasubramanian, Berglund,
Conlon, Quevedo]

Swiss-cheese Calabi-Yau

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

$$W = W_0; \qquad f_{\text{vis}} = \text{const.}$$

Φ = Re(T) : Volume modulus; a = Im(T): Axion.

1. No-scale a la Large Volume Scenario

[Blumenhagen , Conlon, Krippendorf, Moster, Quevedo]

$$\log(T^{3/2}) \sim 2\pi\xi \sim 10$$

$$m_{3/2} \sim \frac{1}{T^{3/2}}; \;\; m_{\Phi} \sim \frac{1}{T^{9/4}}; \;\; m_{\text{soft}} \sim \frac{1}{T^{3}}$$

$$\sim 10^{11}\text{GeV}; \;\; \sim 10^{7}\text{GeV}; \;\; \sim 1-10\text{TeV}.$$

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

$$W = W_0; \quad f_{\text{vis}} = \text{const.}$$

$1/T^{3/2}$; T fixed.

Φ = Re(T) : Volume modulus;   a = Im(T): Axion.

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1. No-scale a la Large Volume Scenario

$$\boxed{B_a \equiv \mathrm{Br}(\Phi \to 2a) = \frac{1}{2z^2+1}.}$$

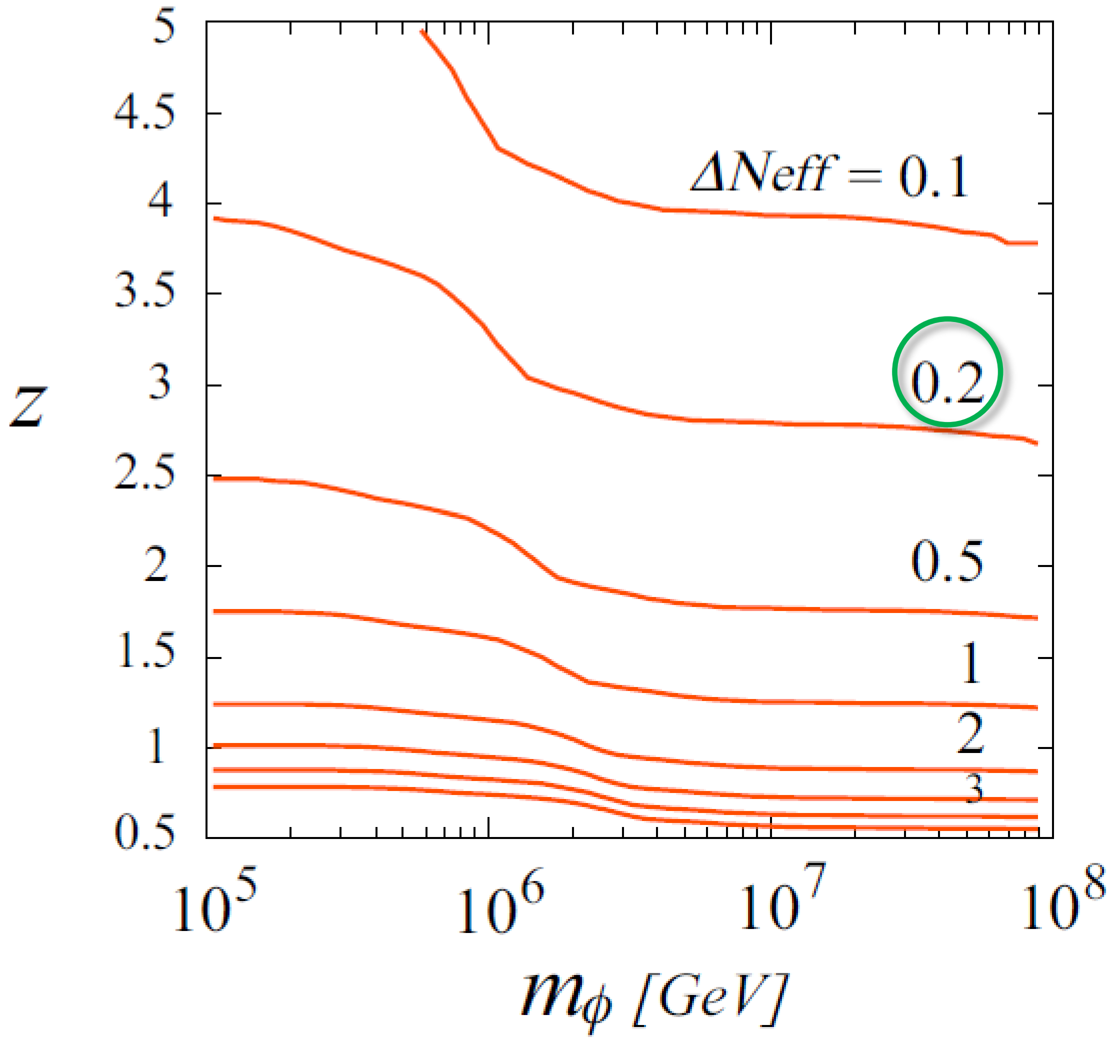
$$\Gamma(\Phi \to 2a) = \frac{1}{48\pi}\frac{m_\Phi^3}{M_\mathrm{P}^2}; \qquad \Gamma(\Phi \to HH) = \frac{2z^2}{48\pi}\frac{m_\Phi^3}{M_\mathrm{P}^2}.$$

$$\mathcal{L} = \frac{z}{\sqrt{6}}(\partial^2\Phi)H_uH_d + \frac{2}{\sqrt{6}}\Phi(\partial a)^2.$$

Φ = Re(T) : Volume modulus;   a = Im(T): Axion.

ΔN_{eff} in (m_Φ, z)

[TH, Takahashi]



$\Delta N_{eff} \sim 0.2$:

$z \sim 3$

or

Many Higgses

(MSSM extension)

Mass and momentum

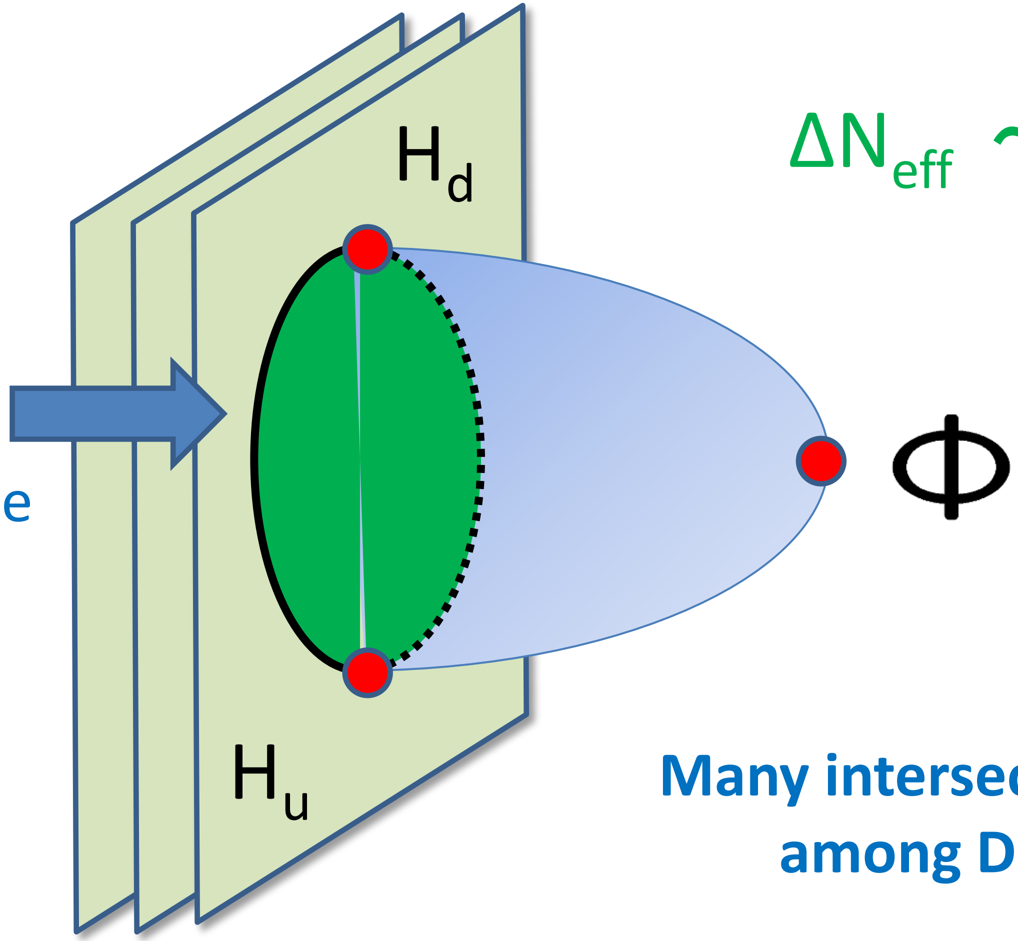
- $m_a \sim e^{-2\pi T} \sim 10^{-100000}$ eV ,

- Decoupled from the SM: $f_a \geqq M_{Pl}$

- $P_a \sim 0.1$ -1 keV (today)

Implication in string theory?

$$\mathcal{L} = z(\partial^2\Phi)H_uH_d$$



$\Delta N_{\rm eff} \sim 0.2$

z∼3:

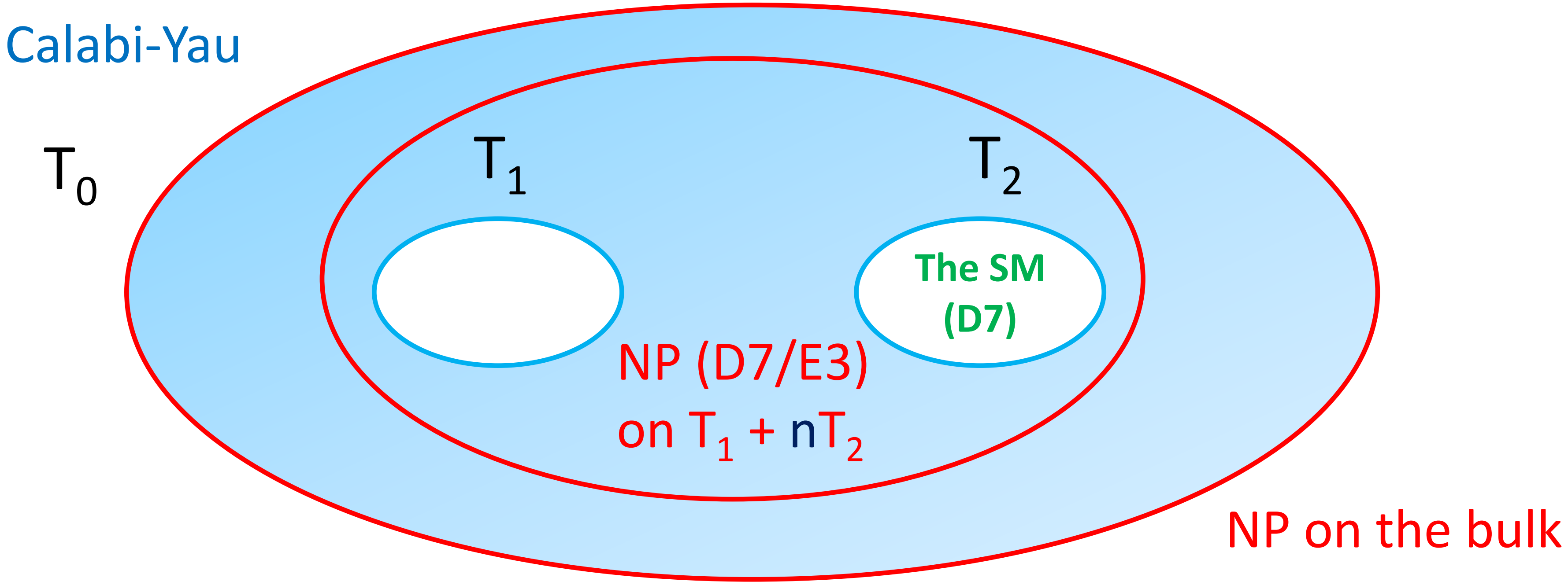
Strong bulk-brane coupling.

(z =1 for a Gauge-Higgs Unification)

Many intersections (~ 6-9) among D-branes?

2. Ex-dim with two holes

[Choi, Jeong]



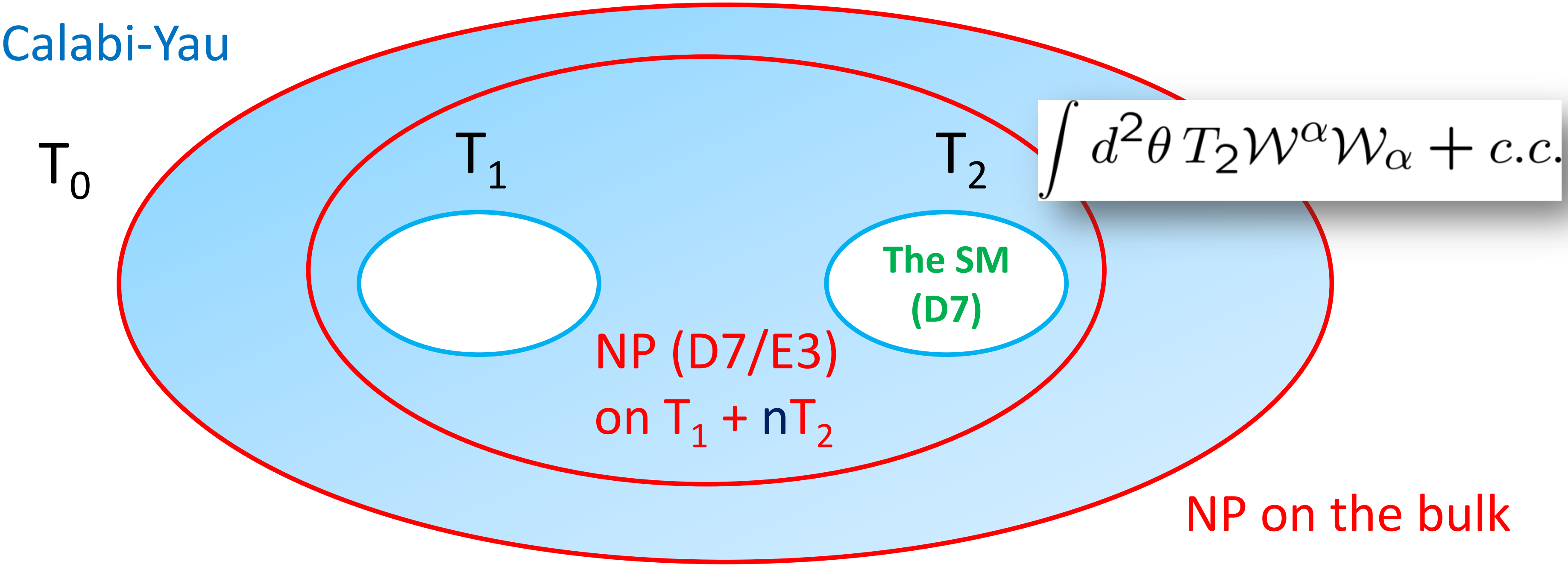
$$K_{\text{moduli}} = -2\log(\mathcal{V}); \qquad \mathcal{V} = (T_0 + T_0^\dagger)^{3/2} - \kappa_1(T_1 + T_1^\dagger)^{3/2} - \kappa_2(T_2 + T_2^\dagger)^{3/2},$$

$$W_{\text{moduli}} = W_0 + Ae^{-\alpha T_0} + Be^{-\beta(T_1 + nT_2)}; \qquad \alpha = \frac{2\pi}{N}, \quad \beta = \frac{2\pi}{M}.$$

2. Ex-dim with two holes

$$\boxed{T = nT_1 - T_2 : \text{ QCD Axion!}}$$

[Choi, Jeong]



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2. Ex-dim with two holes: Stabilization

$$\boxed{T = nT_1 - T_2 : \text{ QCD Axion!}}$$

[Choi, Jeong]

- KKLT stabilization : $D_{T_0}W \simeq D_{T_1+nT_2}W \simeq \partial_T K \simeq 0.$

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- KKLT stabilization : $D_{T_0}W \simeq D_{T_1+nT_2}W \simeq \partial_T K \simeq 0.$
- A sequestered uplifting : $m_s \simeq \sqrt{2}m_{3/2}$; $m_{\tilde{a}} \simeq m_{3/2}$.

$$T = s + ia + \theta\tilde{a} \quad \text{with } f_a \sim M_{\text{string}} \sim M_{\text{GUT}}.$$

$$K_{\text{moduli}} = -2\log(\mathcal{V}); \qquad \mathcal{V} = (T_0 + T_0^\dagger)^{3/2} - \kappa_1(T_1 + T_1^\dagger)^{3/2} - \kappa_2(T_2 + T_2^\dagger)^{3/2},$$

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2. Ex-dim with two holes: Stabilization

$$\boxed{T = nT_1 - T_2 : \ \text{QCD Axion!}}$$

[Choi, Jeong]

- KKLT stabilization : $D_{T_0}W \simeq D_{T_1+nT_2}W \simeq \partial_T K \simeq 0.$
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$$T = s + ia + \theta\tilde{a} \quad \text{with } f_a \sim M_{\text{string}} \sim M_{\text{GUT}}.$$

- Mirage type soft masses : $m_{\text{soft}} \sim \frac{m_{3/2}}{4\pi^2} \sim 1 - 10\text{TeV}.$

$$K_{\text{moduli}} = -2\log(\mathcal{V}); \qquad \mathcal{V} = (T_0 + T_0^\dagger)^{3/2} - \kappa_1(T_1 + T_1^\dagger)^{3/2} - \kappa_2(T_2 + T_2^\dagger)^{3/2},$$

$$W_{\text{moduli}} = W_0 + Ae^{-\alpha T_0} + Be^{-\beta(T_1+nT_2)}; \qquad \alpha = \frac{2\pi}{N}, \quad \beta = \frac{2\pi}{M}.$$

2. Ex-dim with two holes: Decay

[TH, Nakayama, Takahashi]

- Saxion-decay into QCD axions; can be suppressed!

$$\mathcal{L} = K_{TT\bar{T}} s \, (\partial a)^2;$$

$$K_{TT\bar{T}} \propto (n^3 \kappa_1^2 - \kappa_2^2)$$

$$\Gamma_a \simeq \frac{(n^3 {\kappa_1}^2 - {\kappa_2}^2)^2}{768 \pi {\kappa_2}^3} \frac{M_S^3}{M_P^2} \quad ;$$

$$m_s \simeq \sqrt{2} m_{3/2} \sim 100 \text{TeV};$$

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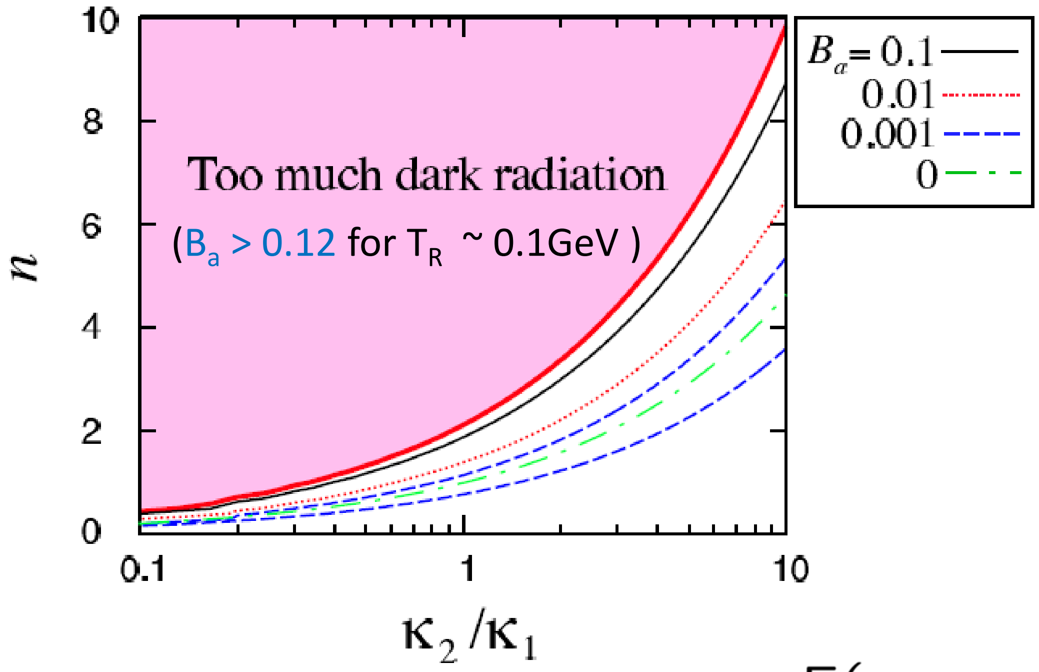

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$$\Gamma(s \to gg) + \Gamma(s \to \tilde{g}\tilde{g}) \simeq N_g \frac{\kappa_2}{32\pi}\frac{M_S^3}{M_P^2}$$

$m_s \simeq \sqrt{2} m_{3/2} \sim 100\text{TeV};$ N_g = 12 for the MSSM.

Mass and momentum if exists

- $m_a \sim 10^{-10}$ eV ,
- $f_a \sim M_{GUT} \sim 10^{16}$ GeV.
- $P_a \sim 0.1$ -1 keV (today)

2. Ex-dim with two holes: Decay

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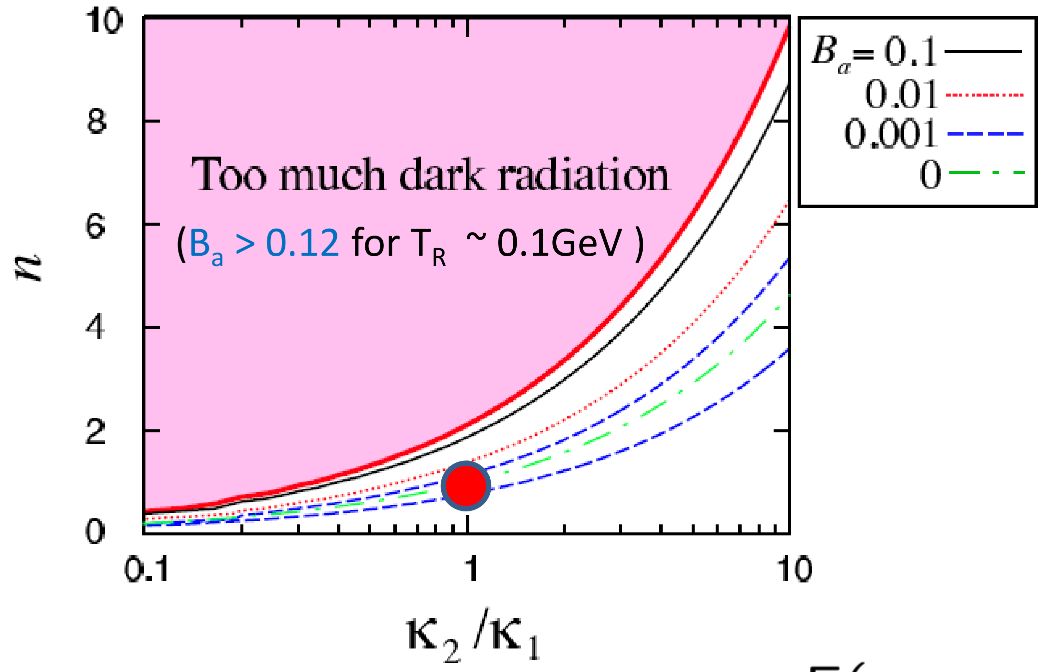

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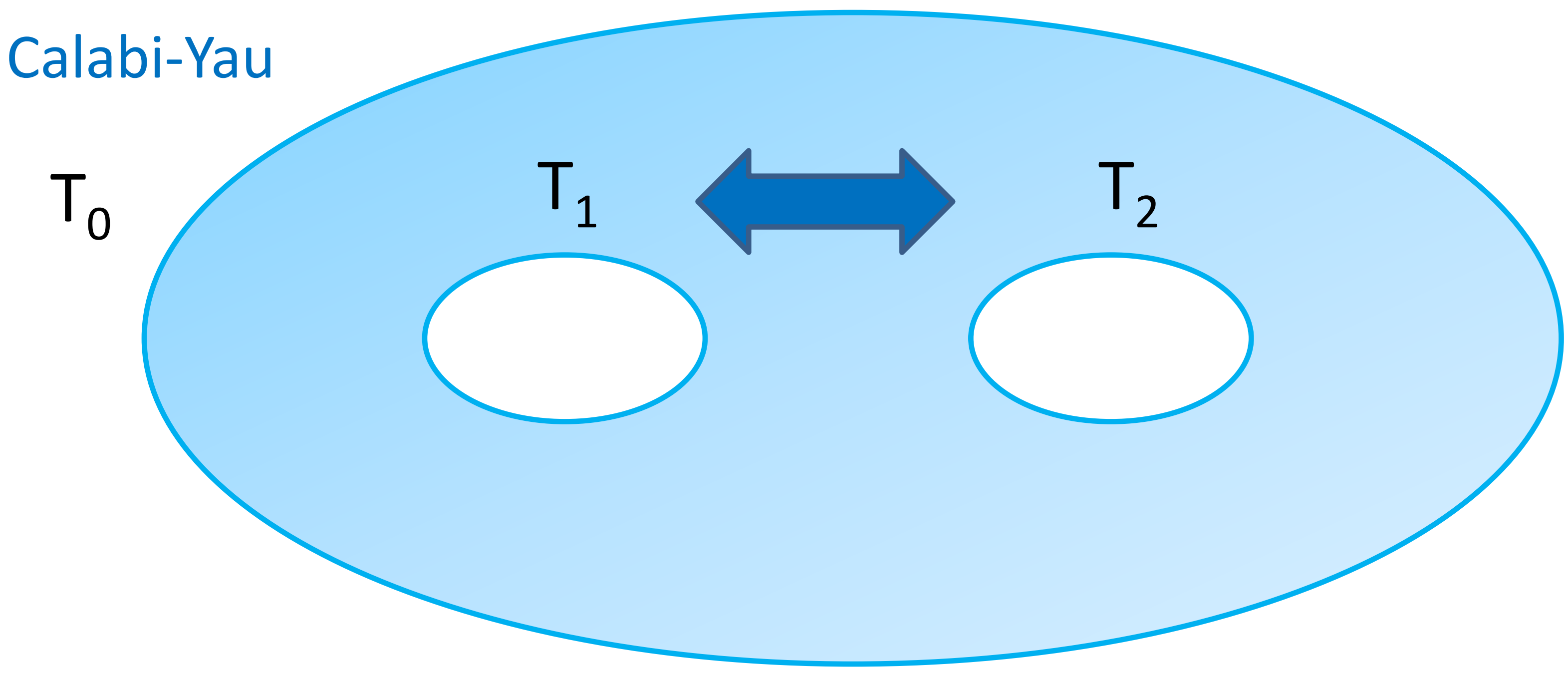
$m_s \simeq \sqrt{2} m_{3/2} \sim 100\text{TeV};$ N_g = 12 for the MSSM.

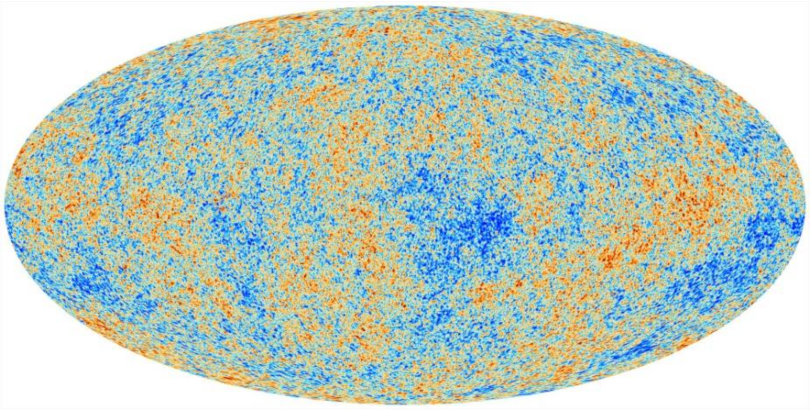
Symmetric Ex-dim: $T_1 \Leftrightarrow T_2$

$\Delta N_{eff} < 0.1$



Conclusion

Cosmological test for string models



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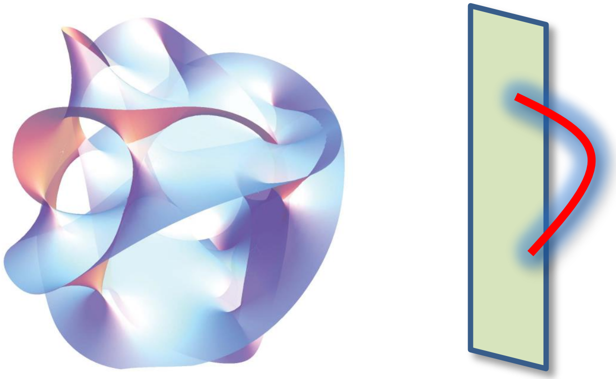


Ex-dim. + D-branes

Axionic dark radiation (= relativistic DM):

$\Delta N_{eff} = O(0.1)$

Key: Moduli problem in reheating

$$\Phi \to aa$$

Φ: Moduli/Inflaton   a: Axion

Axionic dark radiation exists

even for $m_\Phi >> 100$TeV.

Discussions on axion mass

Shift symmetry or $U(1)_{PQ}$ can be broken (to Z_N) by

- Flux compactifications/torsional geometry
- Stringy instantons (NOT QCD)
  - – Light axion might appear, e.g., when

Adjoint states:

$$h^{1,0}(S),\ \ h^{2,0}(S) \neq 0$$

S: 4-cycle on CY

or

Many chiral states:

$$\mathrm{Index}(\mathcal{D}) \gg 1.$$

D: Dirac operator on a D-brane.

Thank you!

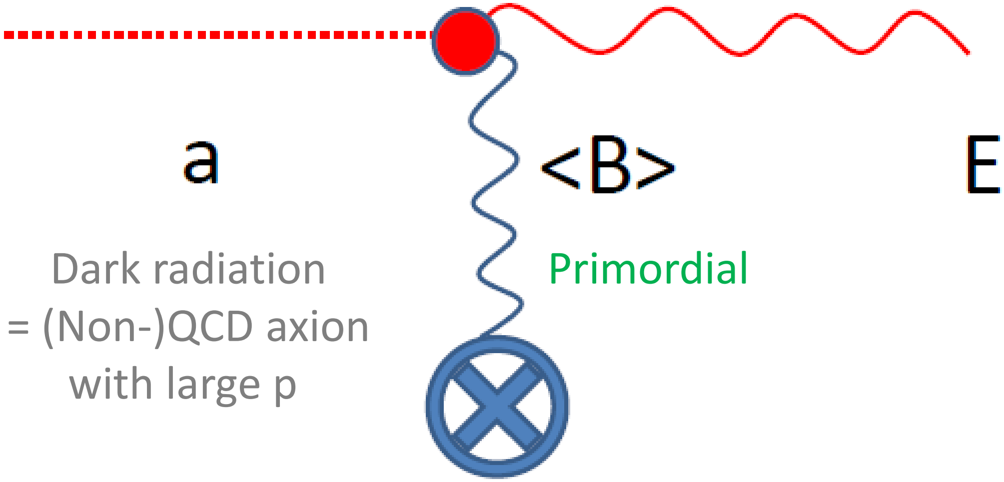
Backup

Constraint on axion dark radiation

1306.6518 **[TH, Nakayama, Takahashi]**

- Axion-photon conversion in the early universe

$$\mathcal{L} = -\frac{1}{4} g_a a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Axion-photon conversion

$$\mathcal{L} = -\frac{1}{4} g_a a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_a a \vec{E} \boxed{\vec{B}}$$

Axions mix with photons in the presence of magnetic field.

$$M_{ij}^2 = \begin{array}{cc} \begin{array}{cc} \gamma & a \end{array} & \\ \left(\begin{array}{cc} \omega_p^2 & \boxed{-g_a B E} \\ \boxed{-g_a B E} & m_a^2 \end{array}\right) & \begin{array}{c} \gamma \\ a \end{array} \end{array}$$

$\omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \simeq 2 \times 10^{-14}\,\mathrm{eV}\,(1+z)^{3/2} X_e^{1/2}$: Plasma frequency

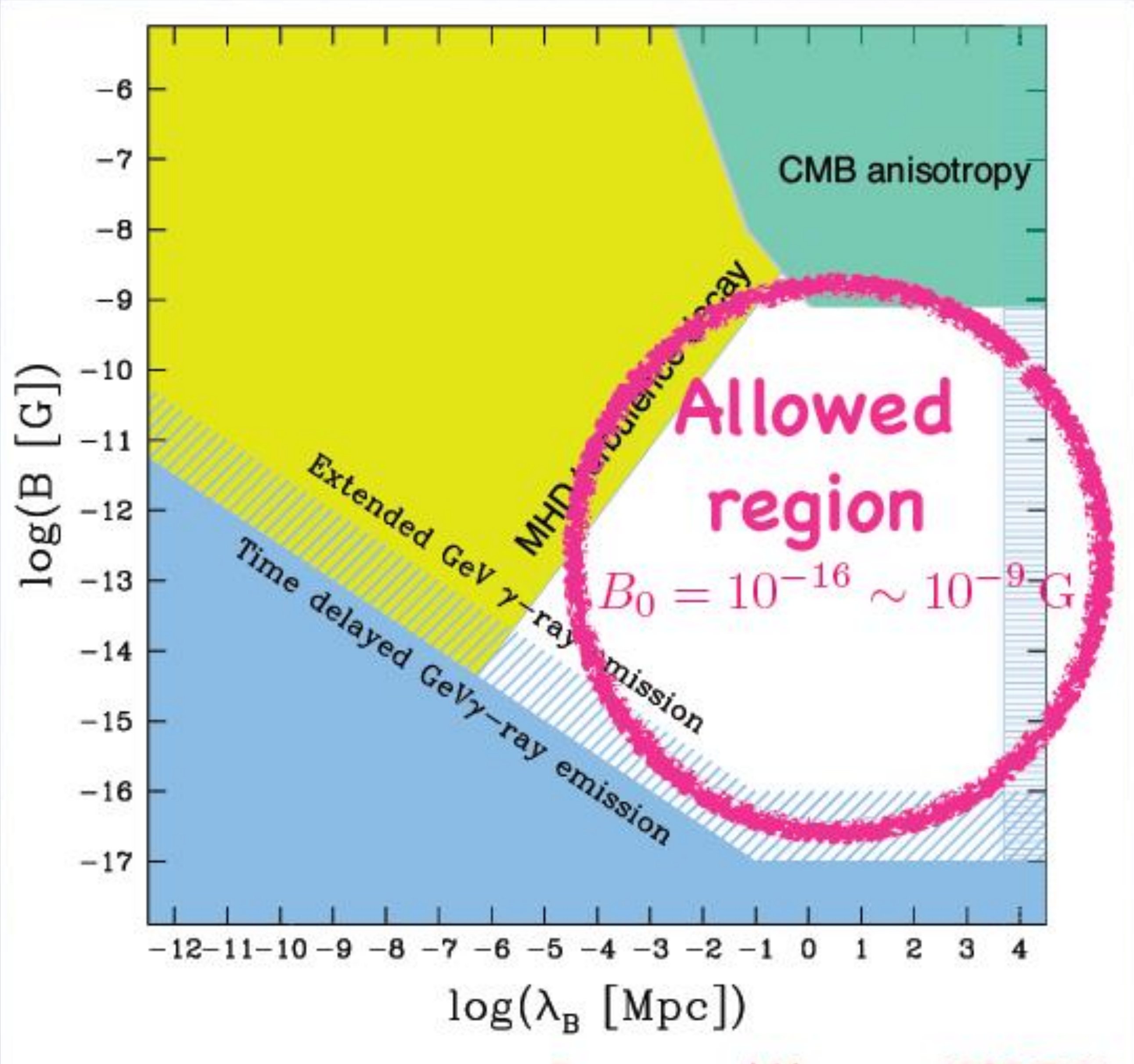
E : Axion energy

Resonant and non-resonant conversion take place.

Yanagida and Yoshimura `88, Sikivie `83

The conversion rate depends on B0.

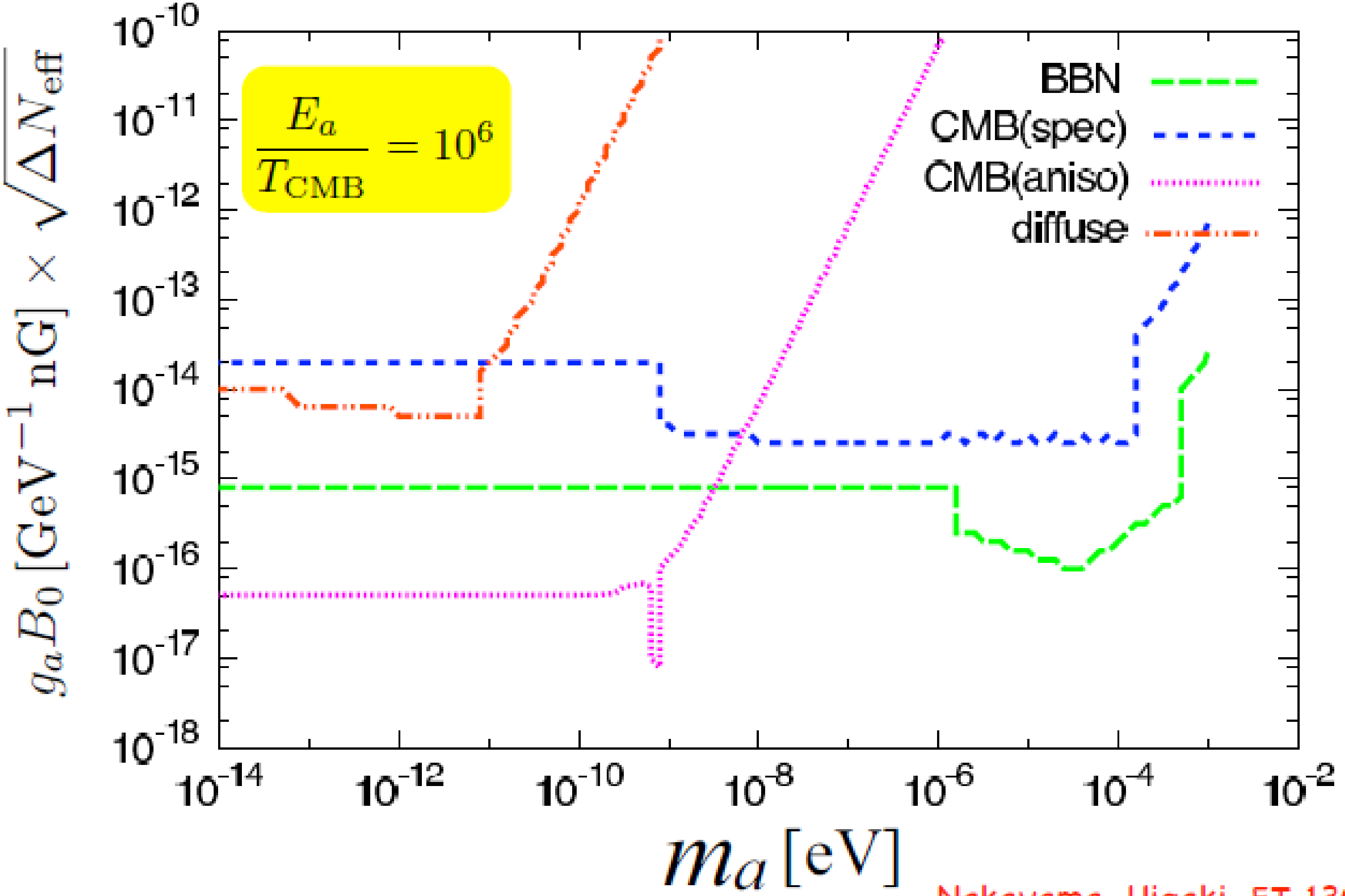
Intergalactic magnetic field



Allowed region

$B_0 = 10^{-16} \sim 10^{-9}\,\mathrm{G}$

Durrer and Neronov 1303.7121



Nakayama, Higaki, FT 1306.6518

Typically, $g_a \lesssim 10^{-16}\,\mathrm{GeV}^{-1}\left(\frac{B_0}{1\,\mathrm{nG}}\right)^{-1}$

for $\Delta N_{\rm eff} = \mathcal{O}(0.1)$

Radiation production (Main)

- Φ decays into Higgs via Giudice-Masiero-term:

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

$$\Gamma(\Phi \to HH) = \frac{m_\Phi^3}{8\pi} \frac{g_T^2}{Z_u Z_d K_{T\bar{T}}}$$

- Φ decays into gauge fields via gauge coupling:

$$\int d^2\theta\, f_{\mathrm{vis}} \mathcal{W}^\alpha \mathcal{W}_\alpha + c.c.$$

N_g = 12 for the MSSM.

$$\Gamma(\Phi \to A_\mu A_\mu) = N_g \frac{m_\Phi^3}{128\pi} \frac{|\partial_T f_{\mathrm{vis}}|^2}{[\mathrm{Re}(f_{\mathrm{vis}})]^2 K_{T\bar{T}}}$$

Solutions

[TH, Nakayama, Takahashi]
See also **[Burgess, Cicoli, Quevedo]**

- Suppress the Φ-a coupling:
  - Many visible modes/ geometry/ just open string axions
- Make (all closed string) axions massive:
  - $U(1)_A$ stückelberg coupling/ NP effects
- Change the final reheating field:
  - No moduli oscillation/ additional entropy production

Because axions are interesting:

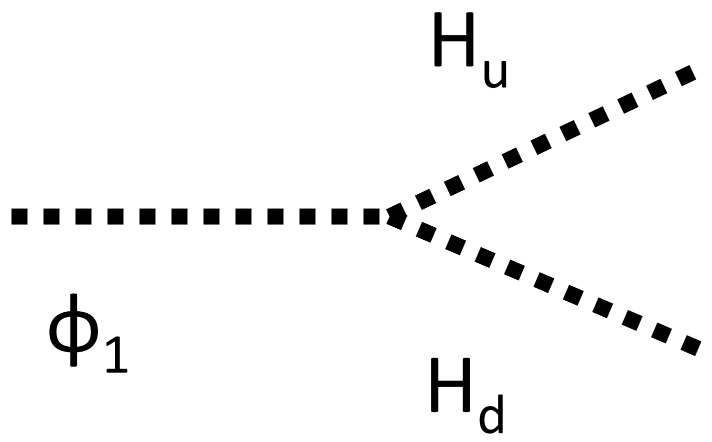
- A solution of strong CP and/or a CDM candidate
- Ubiquitous in the 4D string vacua.

In Large Volume Scenario

Dark matter: Wino
for $m_{soft} = O(1\text{-}10)$ TeV

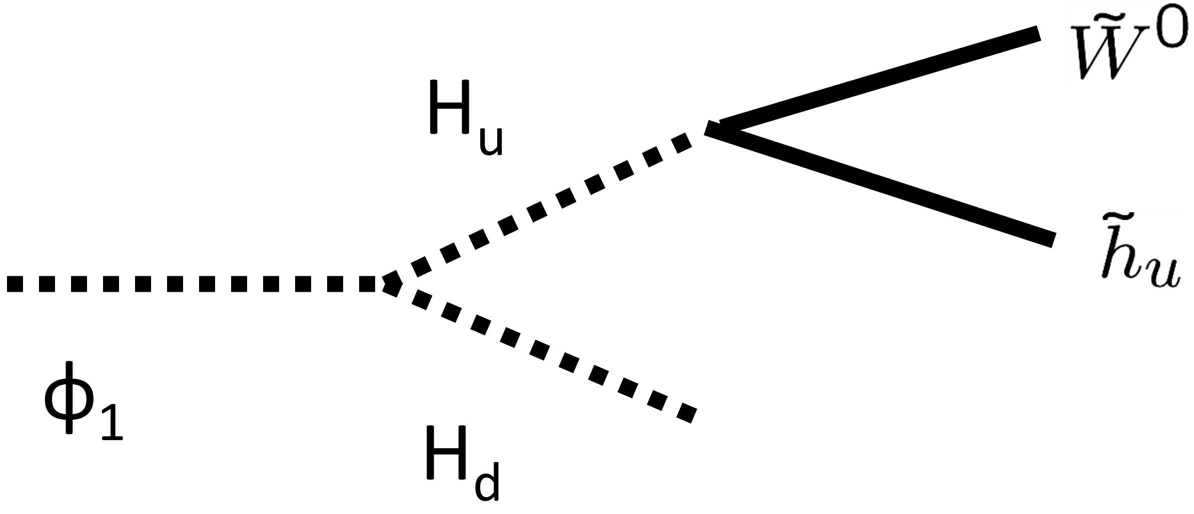
(With assumed R-parity)

Modulus decay



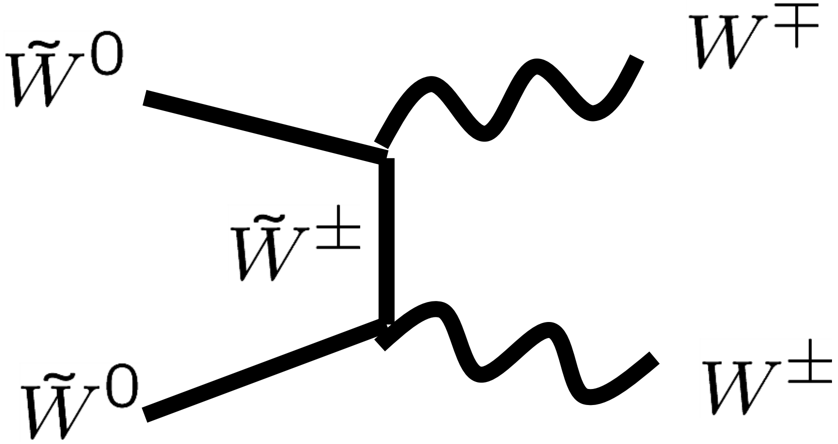
Br = O(1)

Modulus decay into Wino DM



Br = $O(10^{-3})$

Wino DM pair annihilation

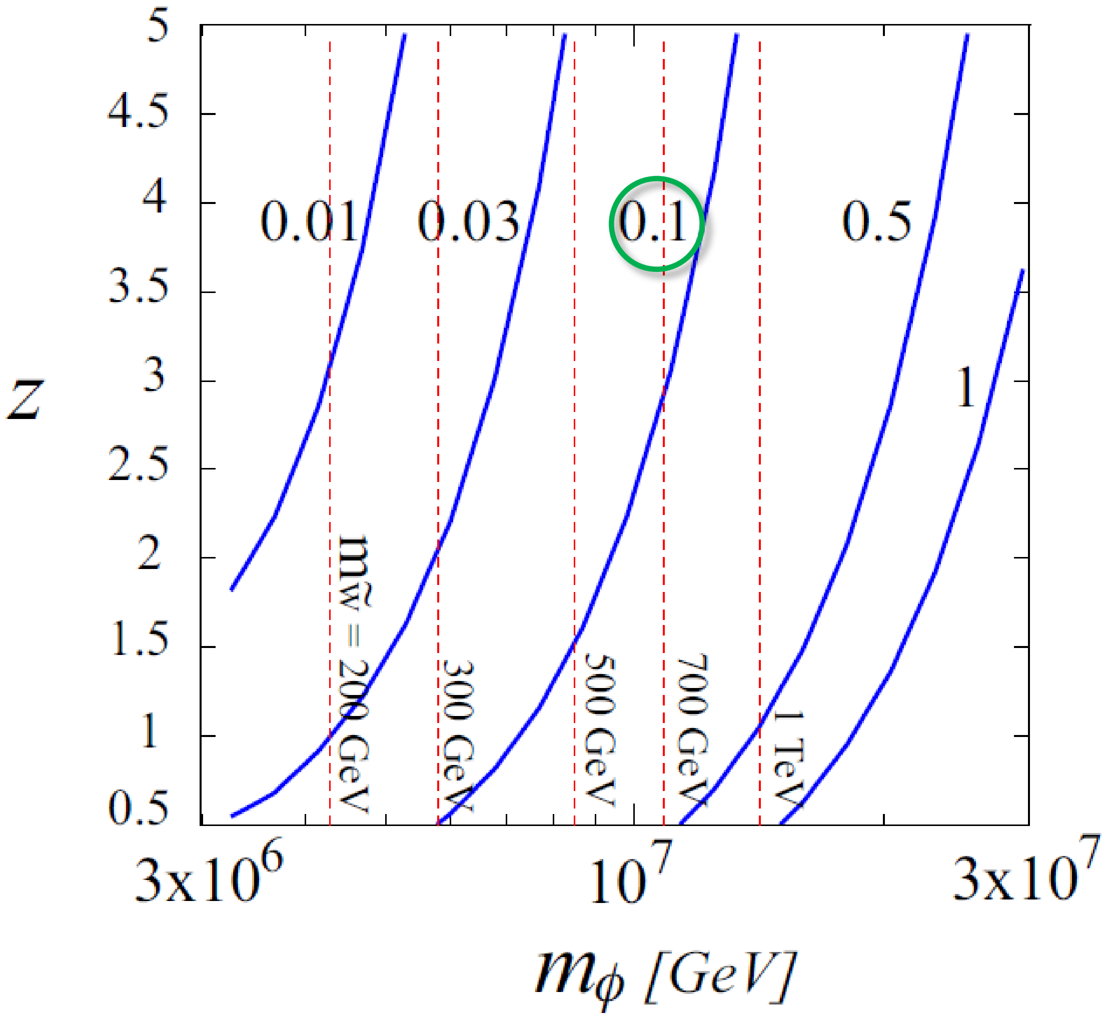


$$\langle \sigma v \rangle \simeq \frac{3g_2^4}{16\pi M_{\tilde{W}^0}^2}$$

$$\Omega_\chi h^2 \simeq 0.16 \left(\frac{g_*(T_d)}{80}\right)^{-\frac{1}{2}} \left(\frac{\langle\sigma v\rangle}{3\times 10^{-8}\,\mathrm{GeV}^{-2}}\right)^{-1} \left(\frac{T_d}{1\,\mathrm{GeV}}\right)^{-1} \left(\frac{m_\chi}{500\,\mathrm{GeV}}\right)$$

These process hardly depends on the branching fraction (> 10^{-5}).

$\Omega_{\mathrm{wino}}h^2$ (with $n_H = 1$)



$(\Omega_{\mathrm{CDM}}h^2)^{\mathrm{obs}} \sim 0.1$

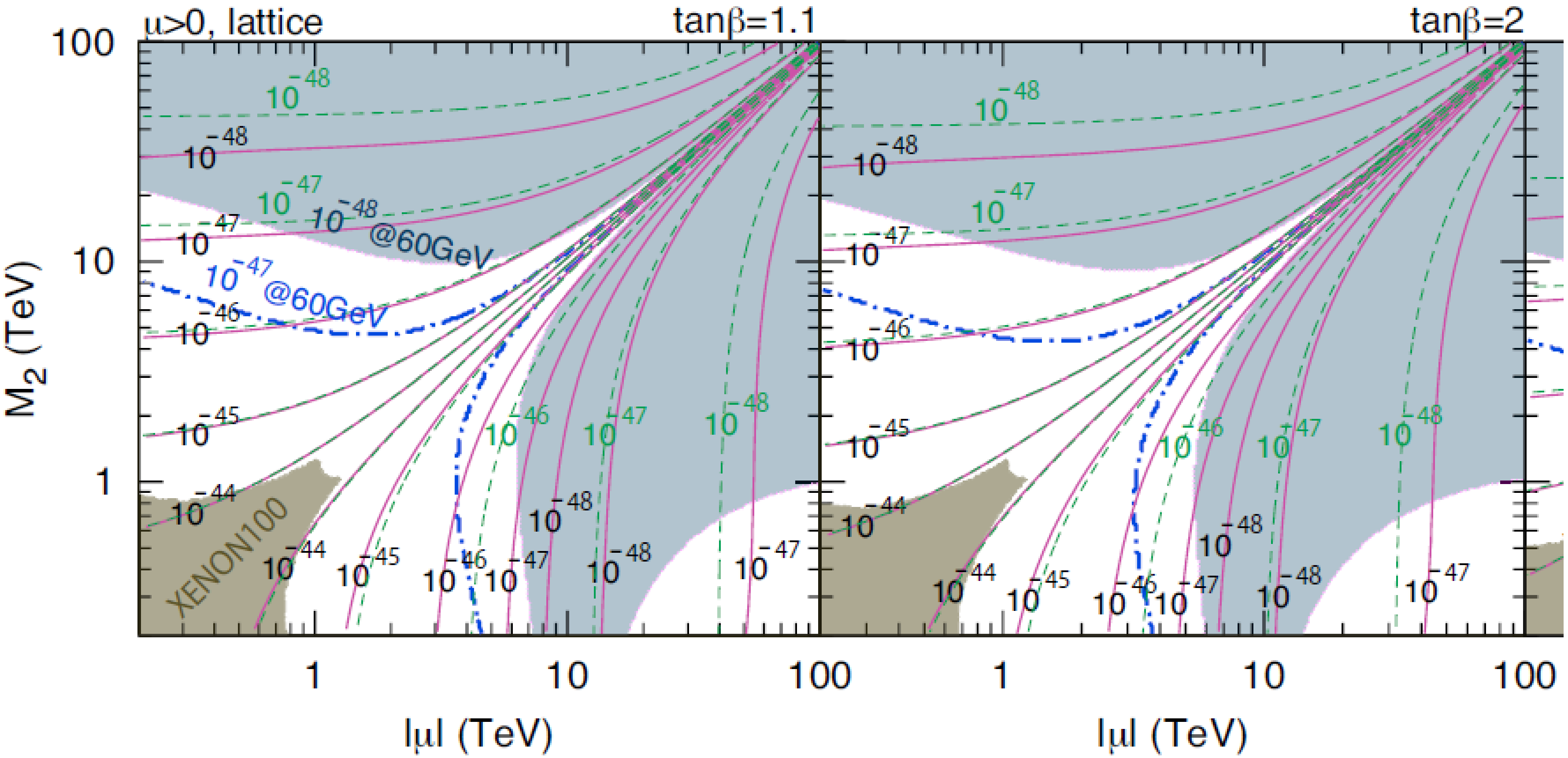
For $z \sim 3$, $\Delta N_{\mathrm{eff}} \sim 0.2$

$m_{\mathrm{Wino}} \sim 700\mathrm{GeV}$

$m_{\tilde{W}} = 1/(\log(\mathcal{V})\mathcal{V}^2)$

Constraint on Wino-like DM mass

$700\text{GeV} \sim m_{\text{Wino}} < \mu \sim z\, m_{\text{Wino}}.$



Hisano, Ishiwata, Nagata (2012)