International workshop on grand unified theories

Supersymmetry and cosmology
~ Inflation, gravitino, axion

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Introduction

- Supersymmetry (supergravity)

  promising candidate for physics beyond the standard model → new particles

- Inflation

  New paradigm of cosmology

  support from WMAP exp.

→ Inflationary cosmology in the framework of SUSY

This Talk

- SUSY inflation
- Gravitino Problem
- Axion in SUSY

SUSY Inflation Models

Inflation model in SUSY

- Slow-roll inflation needs flat potential for inflaton field
- Many flat directions in SUSY models
- SUSY keeps flatness of the inflaton potential at quantum level
- However, extra SUSY breaking due to vacuum energy of inflation may cause a problem

→ η-problem

η problem

- Scalar Potential in SUGRA

$$V = e^K \left[\left(\frac{\delta^2 K}{\delta\phi_i \delta\phi^{*j}} \right)^{-1} D_i W D^{*j} W^* - 3|W|^2 \right] + (\text{D Term})$$

K : Kahler potential $= \phi_i \phi^{*i} + \cdots$

W : superpotential

$$D_i W = \frac{\delta W}{\delta \phi_i} + \frac{\delta K}{\delta \phi_i} W$$

- During inflation

$\phi \ll M_p = 1$

$$V \sim (1 + |\phi|^2) V_I \sim V_I + V_I |\phi|^2 \sim V_I + H_I^2 |\phi|^2$$

➡ Hubble induced mass term

$$\eta \equiv (V''/V) \sim V''/H_I^2 \sim O(1) \quad (\Leftrightarrow \ll 1 \text{ for inflation})$$

$\phi > M_p$

➡ $V \sim e^{|\phi|^2} (\ \cdots \ )$ very steep for large field

Solutions to η problem

- Special form for W and K
  - Superpotential is linear in inflaton field

    $$W = F(X)\phi \Rightarrow$$ no Hubble induced term for minimal Kähler

  - Shift Symmetry in Kähler potential

    $$\phi \to \phi + iC \Rightarrow K = f(\phi + \phi^*)$$

    No exp. rise for Im(ϕ)

- Others (D term inflation . . . .)

Chaotic Inflation in Supergravity

MK, Yamaguchi, Yanagida
PRD63 (2001)103514

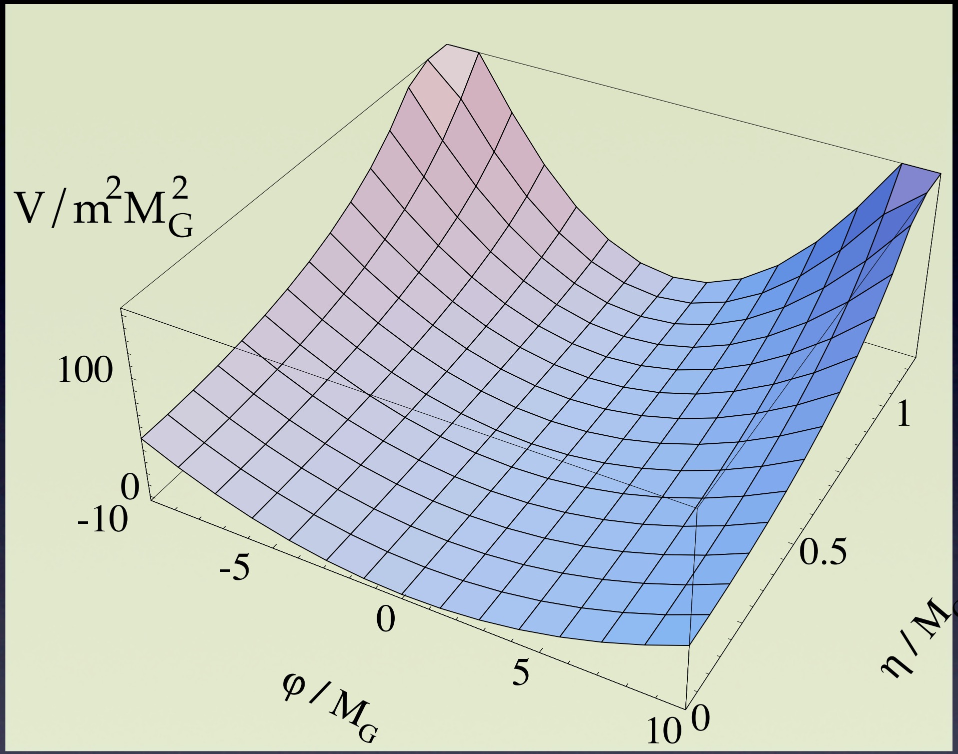
Shift symmetry $\Phi \Rightarrow \Phi + iC$

Kähler potential

$$K = c(\Phi + \Phi^*) + (\Phi + \Phi^*)^2 + |X|^2$$

superpotential

$$W = mX\Phi$$



$$\begin{aligned} V &= (\eta = 0, \varphi, X) \simeq \frac{1}{2} m^2 \varphi^2 + m^2 |X|^2 \\ \Phi &= \eta + i\varphi \end{aligned}$$

spectral index $n_s \simeq 0.96$ consistent with WMAP

Hybrid inflation in supergravity

Copeland et al (1994); Dvali, Shafi, Schaefer (1994); Linde, Riotto (1997)

superpotential

$$W = \lambda S \bar{\Psi}\Psi - \mu^2 S$$

R-charge $S(+2)$ $\bar{\Psi}\Psi(0)$

U(1) gauge int $S(0)$ $\bar{\Psi}(-1)$ $\Psi(+1)$

Kähler potential

$$K = |S|^2 + |\Psi|^2 + |\bar{\Psi}|^2$$

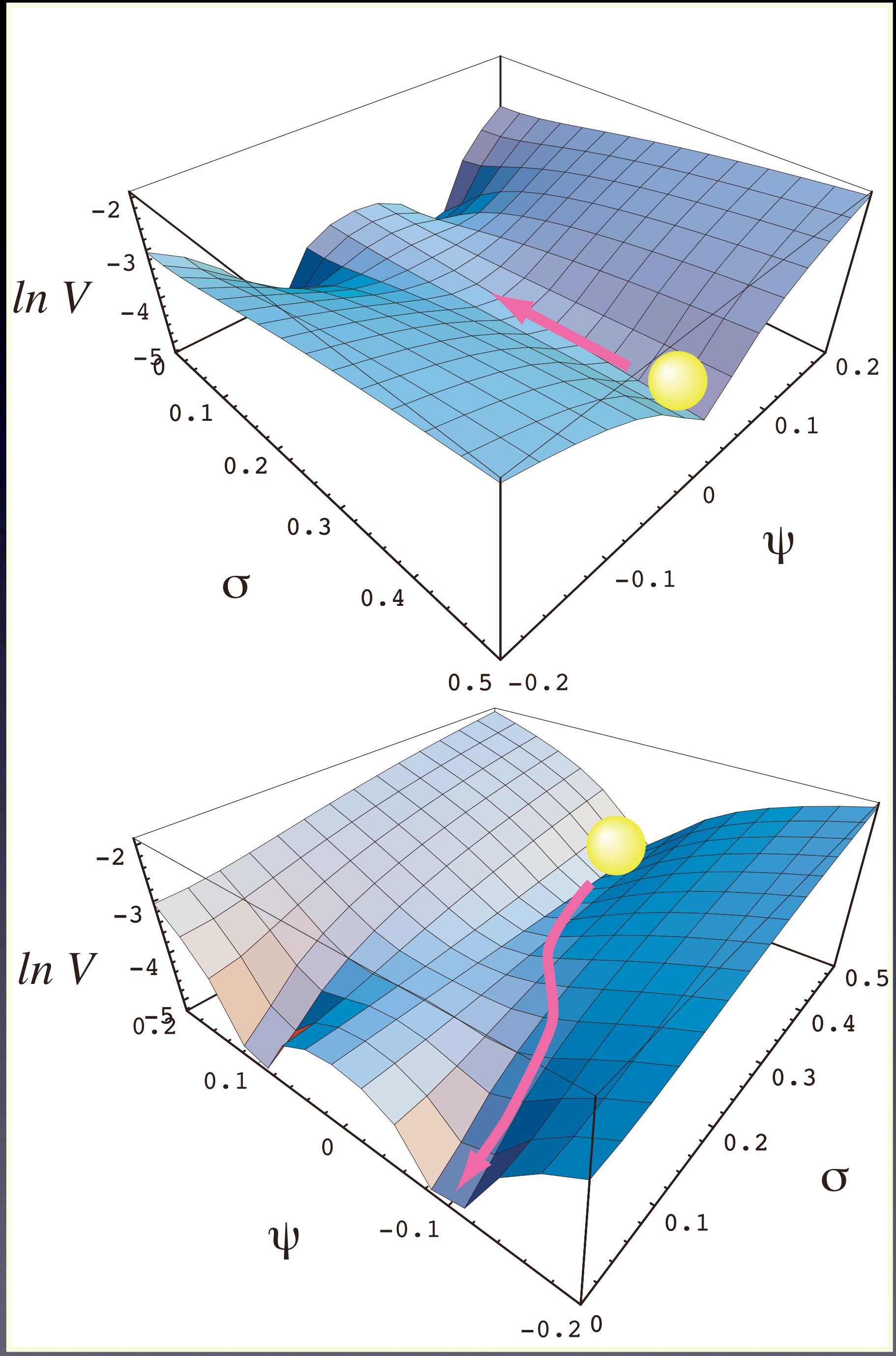
→ scalar potential

$\sigma \equiv ReS/\sqrt{2}$

$\sigma > \sigma_c \equiv \sqrt{2}\mu/\lambda \quad \Rightarrow \quad \Psi = \bar{\Psi} = 0$

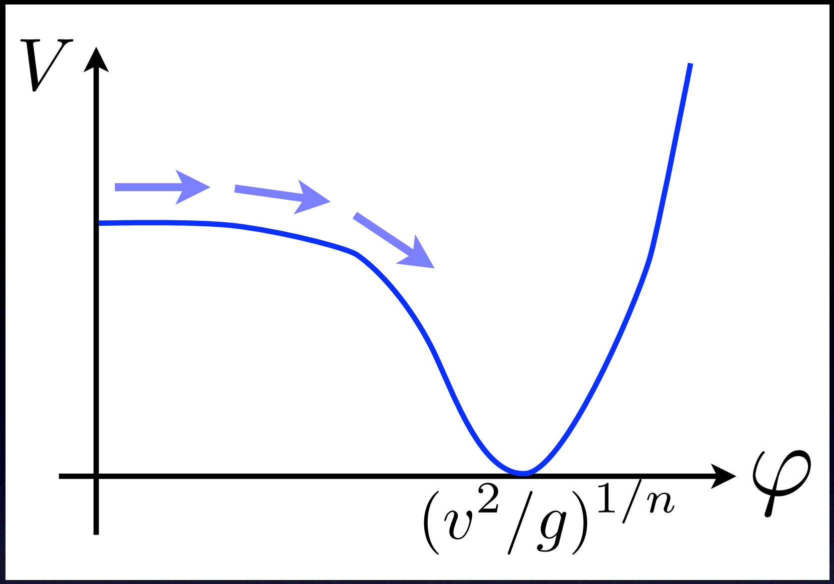
flat potential → inflation

spectral index $n_s \simeq 0.98 - 1.0$



New Inflation

Izawa, Yanagida(1997); Ibe Shinbara, Yanagida (2006)



Superpotential

$$W = v^2\Phi - \frac{g}{n+1}\Phi^{n+1}$$

Kähler potential

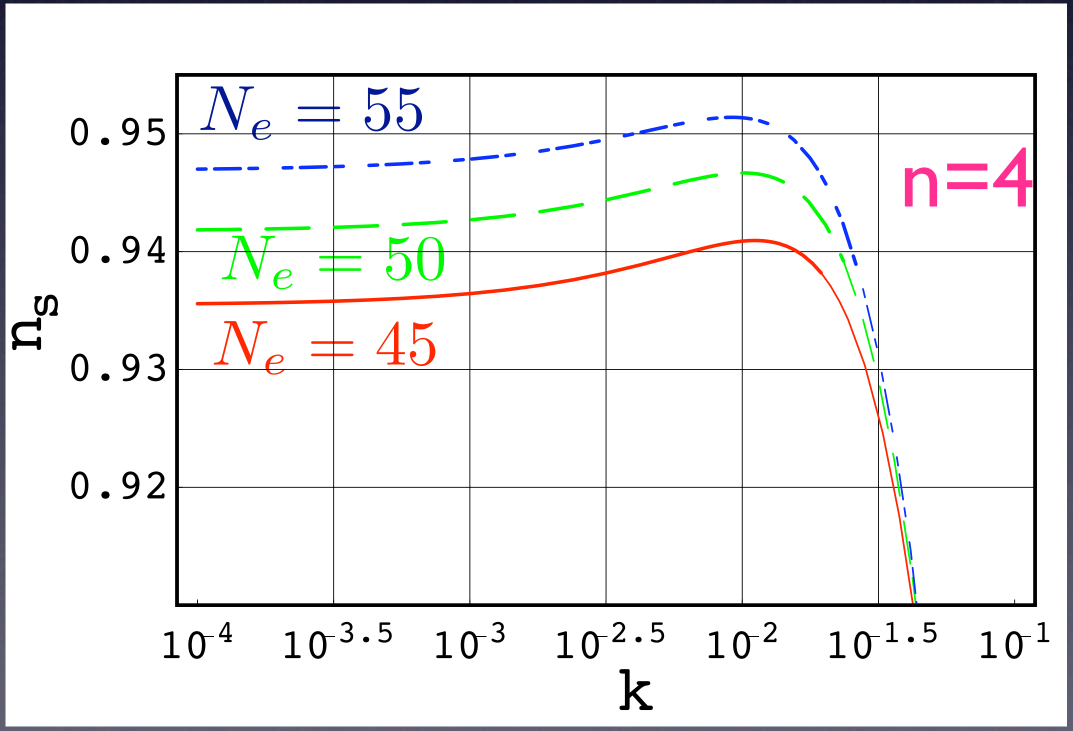
$$K = |\Phi|^2 + \frac{k}{4}|\Phi|^4$$

scalar potential

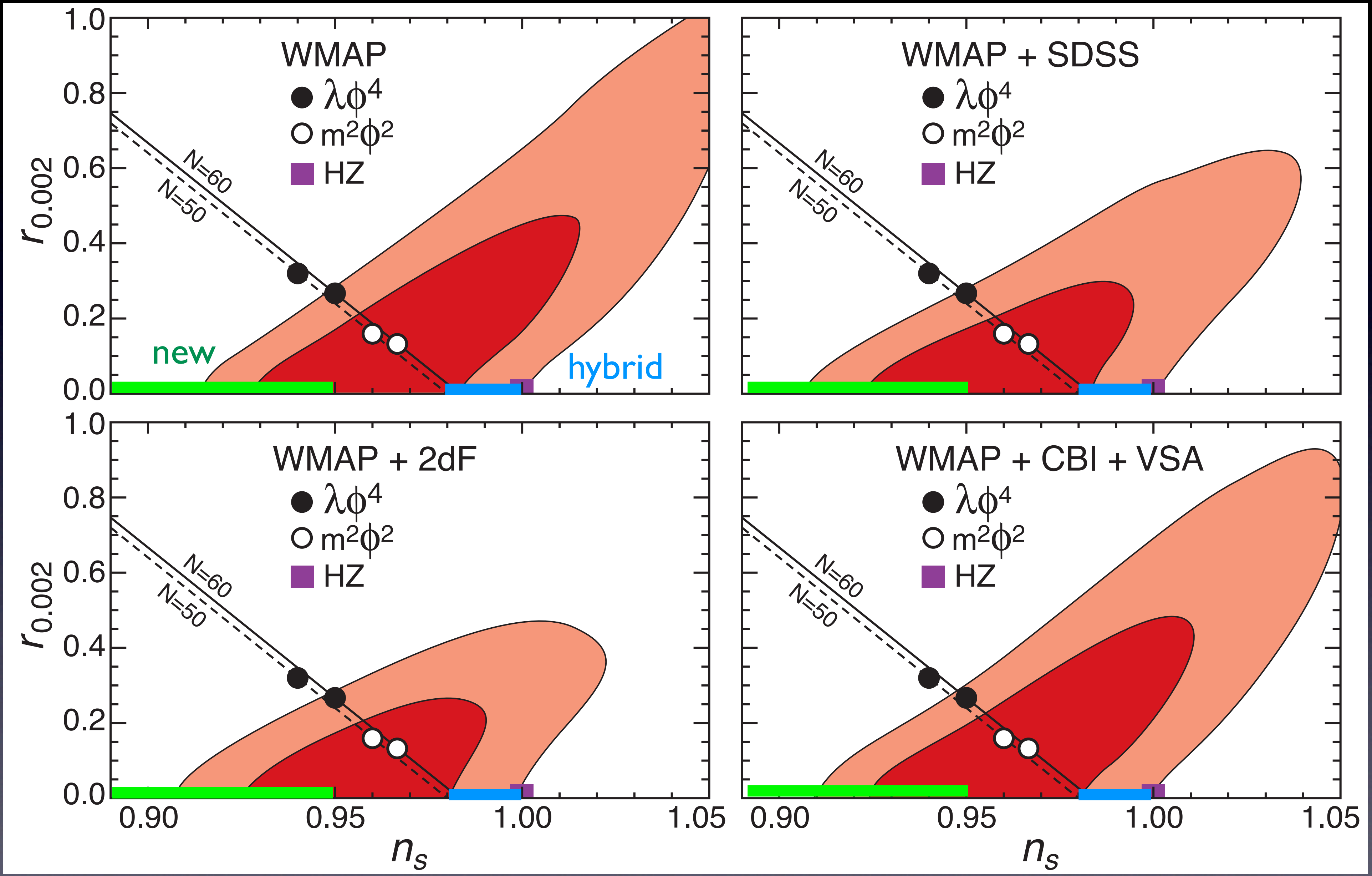
$$V(\varphi) = v^4 - \frac{k}{4}v^4\varphi^2 - \frac{g}{2^{n/2-1}}v^2\varphi^2 + \frac{g^2}{2^n}\varphi^{2n}$$

spectral index

$$n_s \lesssim 0.95$$



WMAP three years data



Spergel et al (2006)

Reheating after inflation

- Reheating takes place through inflaton decay
- The decay rate depends on coupling with other particles → model dependent
- However, the decay through top Yukawa coupling occurs by SUGRA effect $W = Y_t T Q H_u$

Endo, MK, Takahashi, Yanagida (2006)

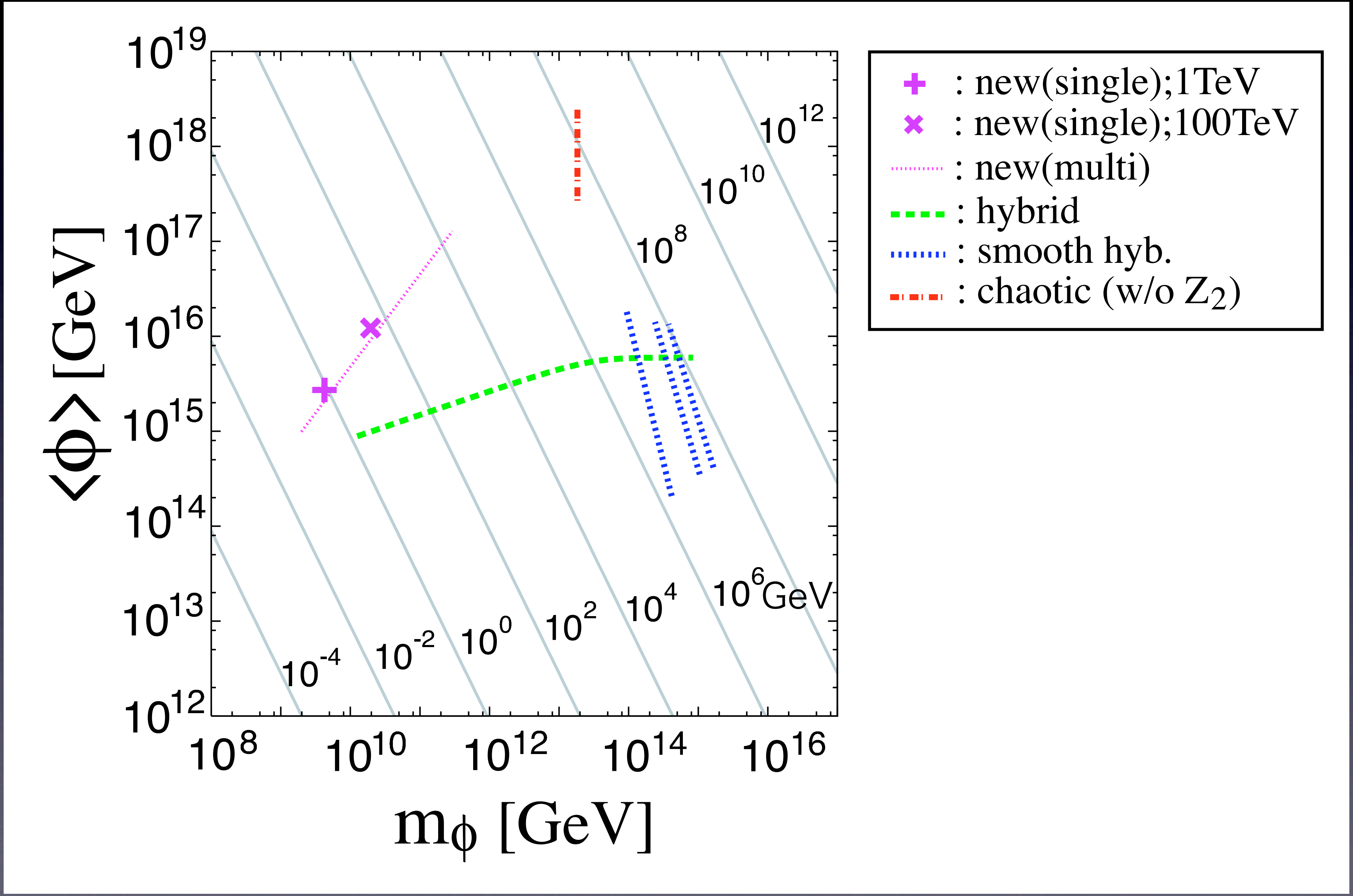
→ model independent

$$\Gamma_T = \frac{3}{128\pi^3}|Y_t|^2 \left(\frac{\langle\phi\rangle}{M_p}\right)^2 \frac{m_\phi^3}{M_p^2}$$

- This gives lower bound on the reheating temperature

Lower bound on reheating temperature

Endo, MK, Takahashi, Yanagida (2006),
Endo, Takahashi, Yanagida (2007)



Gravitino Problem

Gravitino Problem

Gravitino — Superpartner of graviton

$\psi_{3/2}$ ➡ only gravitationally suppressed int.

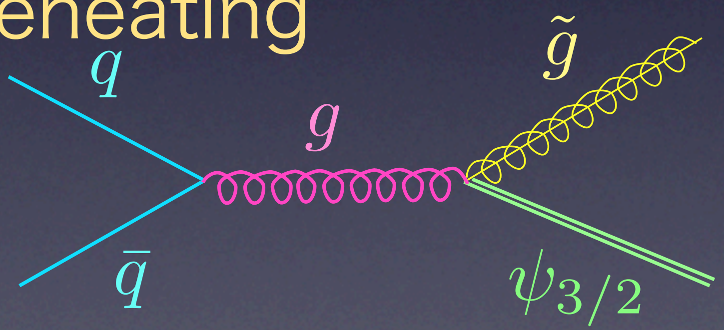
➡ long lifetime

$$\tau(\psi_{3/2} \to \tilde{\gamma} + \gamma) \simeq 4 \times 10^8\,\mathrm{sec} \left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^{-3}$$

Gravitino in Inflationary Universe

gravitinos are produced during reheating

$$Y_{3/2} \equiv \frac{n_{3/2}}{s} \simeq 1.9 \times 10^{-12} \left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)$$



➡ serious cosmological effects

Gravitino Problem

Gravitino Mass

- Gravitino mass depends on mediation mechanism for SUSY breaking
  - gravity mediation ~ SUSY breaking in hidden sector is transferred to observable sector by gravity

$$m_{3/2} \simeq 100 \text{ GeV} - 10 \text{ TeV}$$

  - gauge mediation ~ SUSY breaking in hidden sector is mediated by gauge interaction

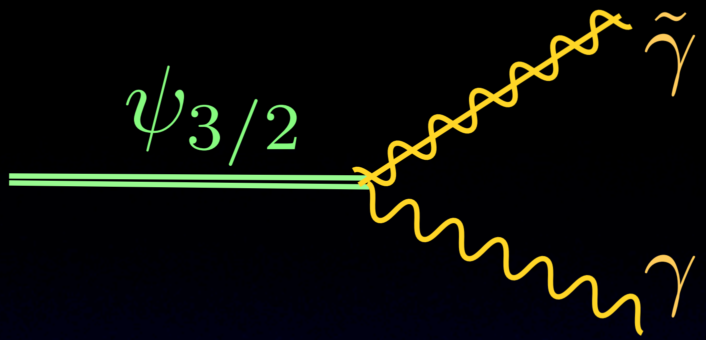
$$m_{3/2} \lesssim 10 \text{ GeV}$$

  - anomaly mediation ~ SUSY breaking in hidden sector is transferred to visible sector through pure gravity effect (superconformal anomaly)

$$m_{3/2} \simeq 100 - 10^3 \text{ TeV}$$

Gravitino Decay and BBN

Gravitino in Gravity and Anomaly Mediated SUSY Breaking



$$m_{3/2} \simeq 100\text{GeV} - 10^3\text{TeV}$$

→ Unstable

- Radiative Decay $\psi_{3/2} \to \tilde{\gamma} + \gamma$

$$\tau(\psi_{3/2} \to \tilde{\gamma} + \gamma) \simeq 4 \times 10^8 \,\text{sec} \left(\frac{m_{3/2}}{100\text{GeV}}\right)^{-3}$$

- Hadronic Decay $\psi_{3/2} \to \tilde{g} + g$

$$\tau(\psi_{3/2} \to \tilde{g} + g) \simeq 6 \times 10^7 \,\text{sec} \left(\frac{m_{3/2}}{100\text{GeV}}\right)^{-3}$$

Decay Products (photons, hadrons)

↓

Serious Effect on Big Bang Nucleosynthesis

↓

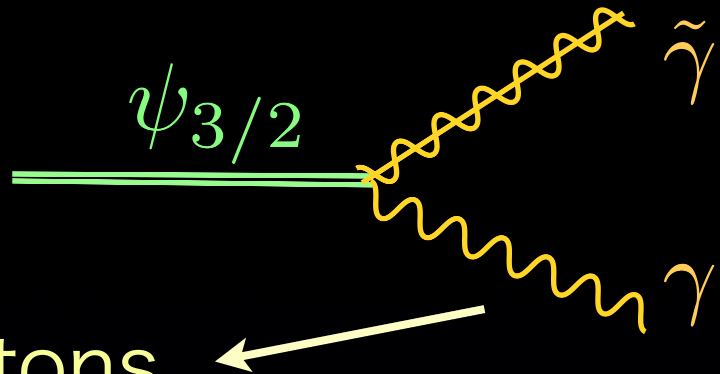
$$Y_{3/2} \equiv \frac{n_{3/2}}{s} \simeq 1.9 \times 10^{-12} \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right)$$

Stringent Constraint on T_R

Ellis, Nanopoulos,Sarkar (1985)
Reno, Seckel (1988)
Dimopoulos et al (1989)
MK, Moroi (1995)
. . . . .

Radiative Decay

Ellis, Nanopoulos,Sarkar (1985)
MK, Moroi (1995), and many others



High Energy Photons

→ Electromagnetic Cascade

→ Many Soft Photons

→ Destroy Light Elements

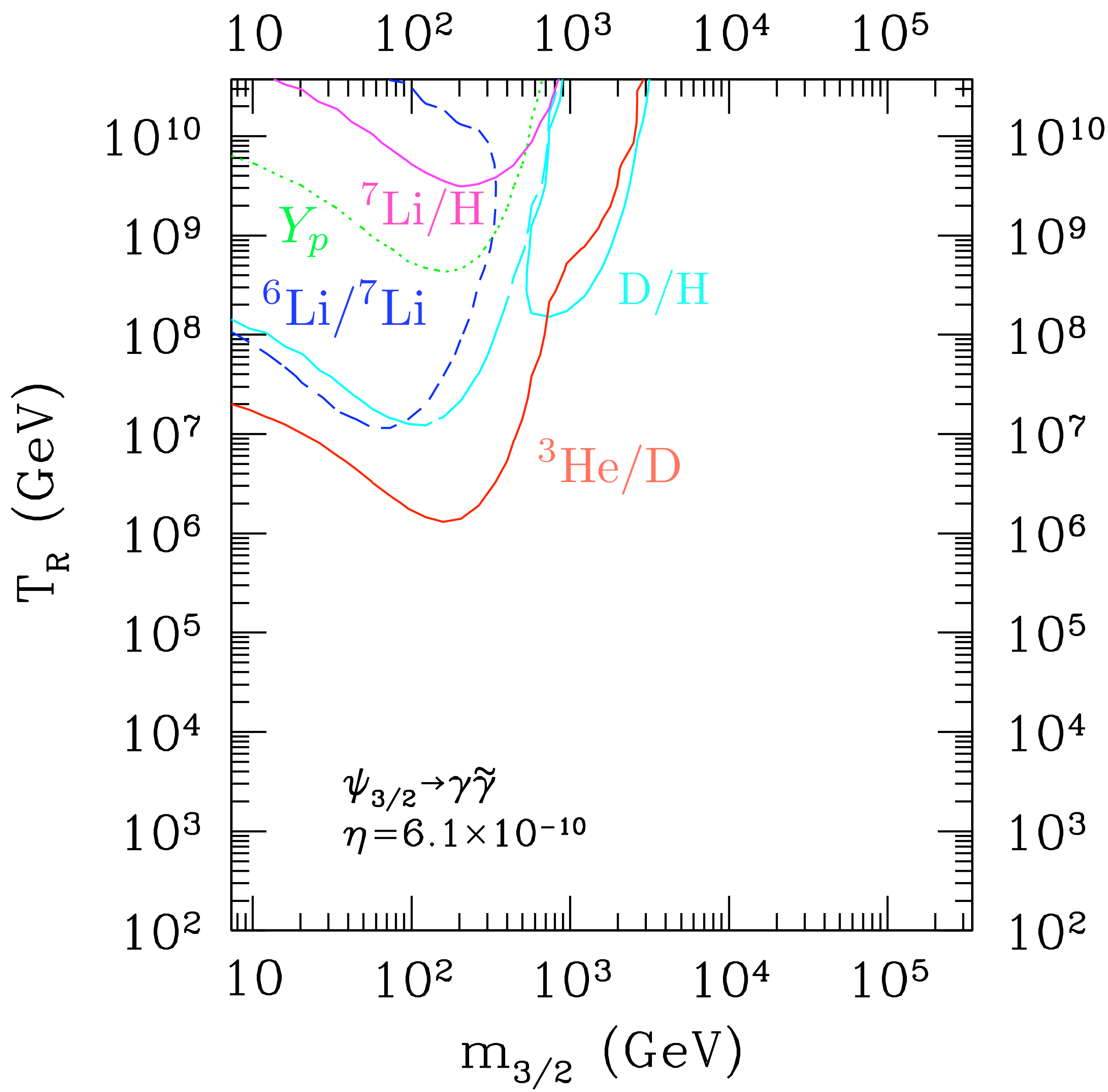
$$\mathrm{D} + \gamma \rightarrow n + p \quad [2.22\ \mathrm{MeV}]$$

$$^{3}\mathrm{He} + \gamma \rightarrow \mathrm{D} + p \quad [5.5\ \mathrm{MeV}]$$

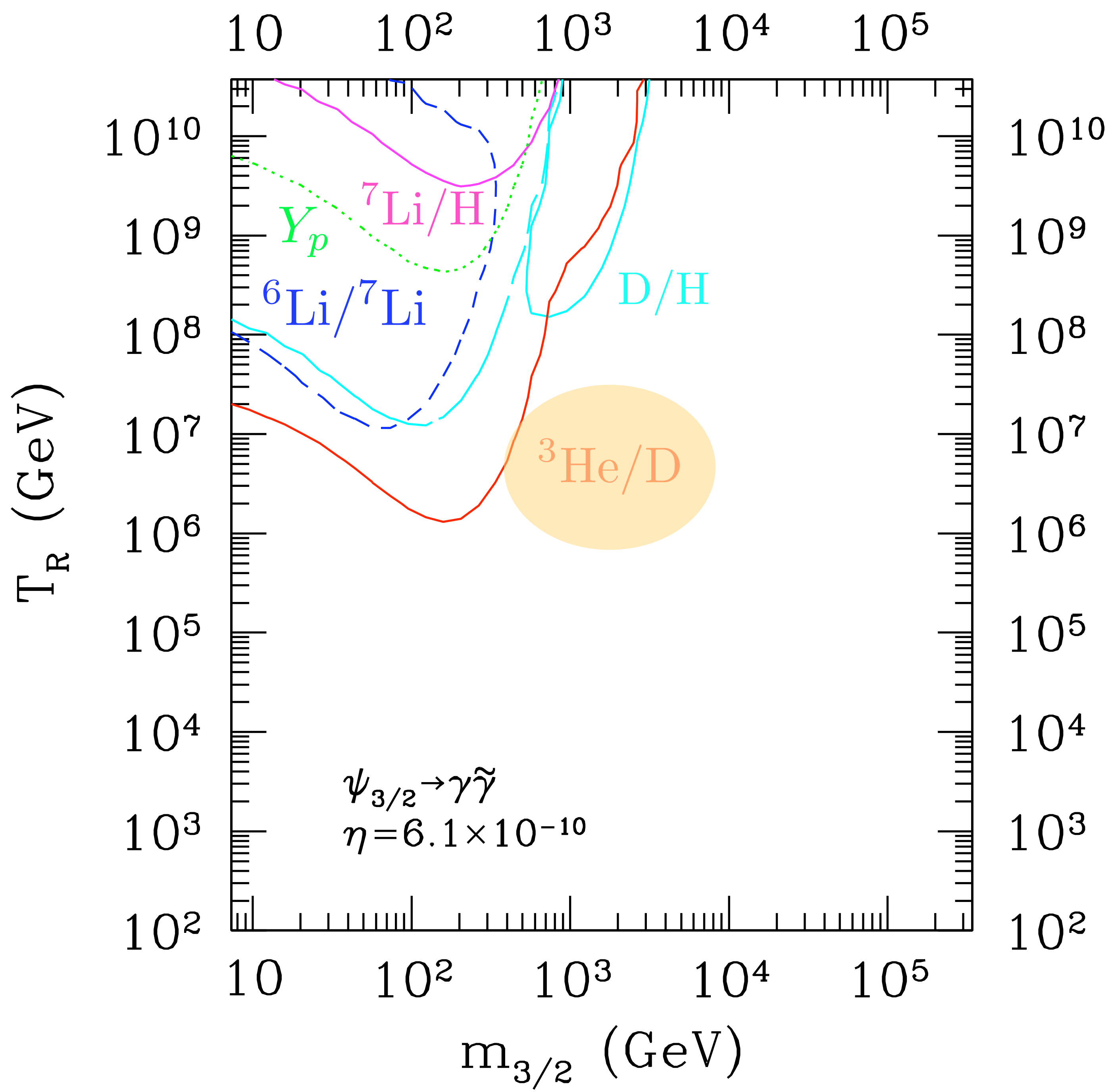
$$^{4}\mathrm{He} + \gamma \rightarrow {}^{3}\mathrm{He} + n \quad [20.5\ \mathrm{MeV}]$$

$$^{4}\mathrm{He} + \gamma \rightarrow \mathrm{D} + n + p \quad [26.1\ \mathrm{MeV}]$$

etc



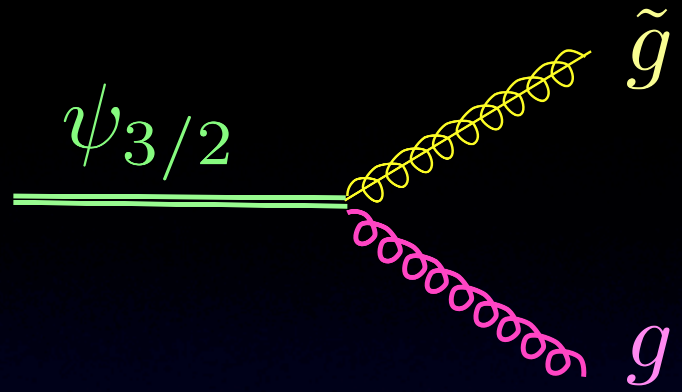
T_R (GeV)
$m_{3/2}$ (GeV)
^{7}Li/H
Y_p
^{6}Li/^{7}Li
D/H
^{3}He/D
$\psi_{3/2}\to\gamma\tilde{\gamma}$
$\eta=6.1\times10^{-10}$



^{7}Li/H
Y_p
^{6}Li/^{7}Li
D/H
^{3}He/D
$\psi_{3/2} \to \gamma\tilde{\gamma}$
$\eta = 6.1 \times 10^{-10}$
T_R (GeV)
$m_{3/2}$ (GeV)
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}

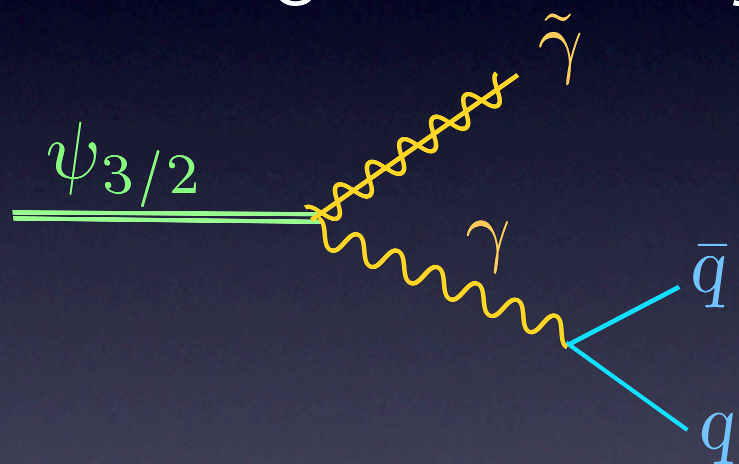
Hadronic Decay

Reno, Seckel (1988)
Dimopoulos et al (1989)
MK, Kohri, Moroi (2005)
Jedamzik (2006)



$$B_h \sim 1$$

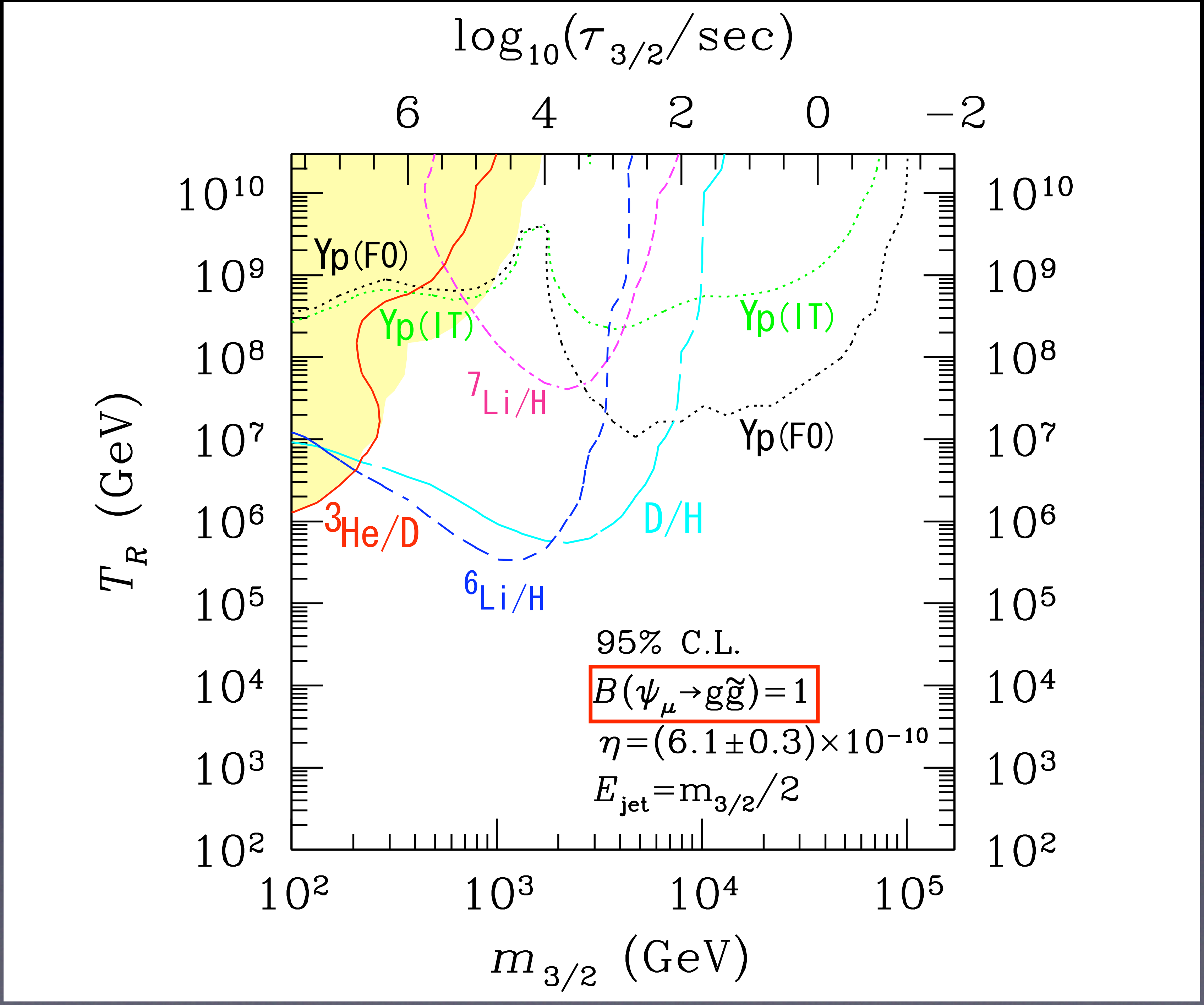
Even if a gravitino only decays into a photino



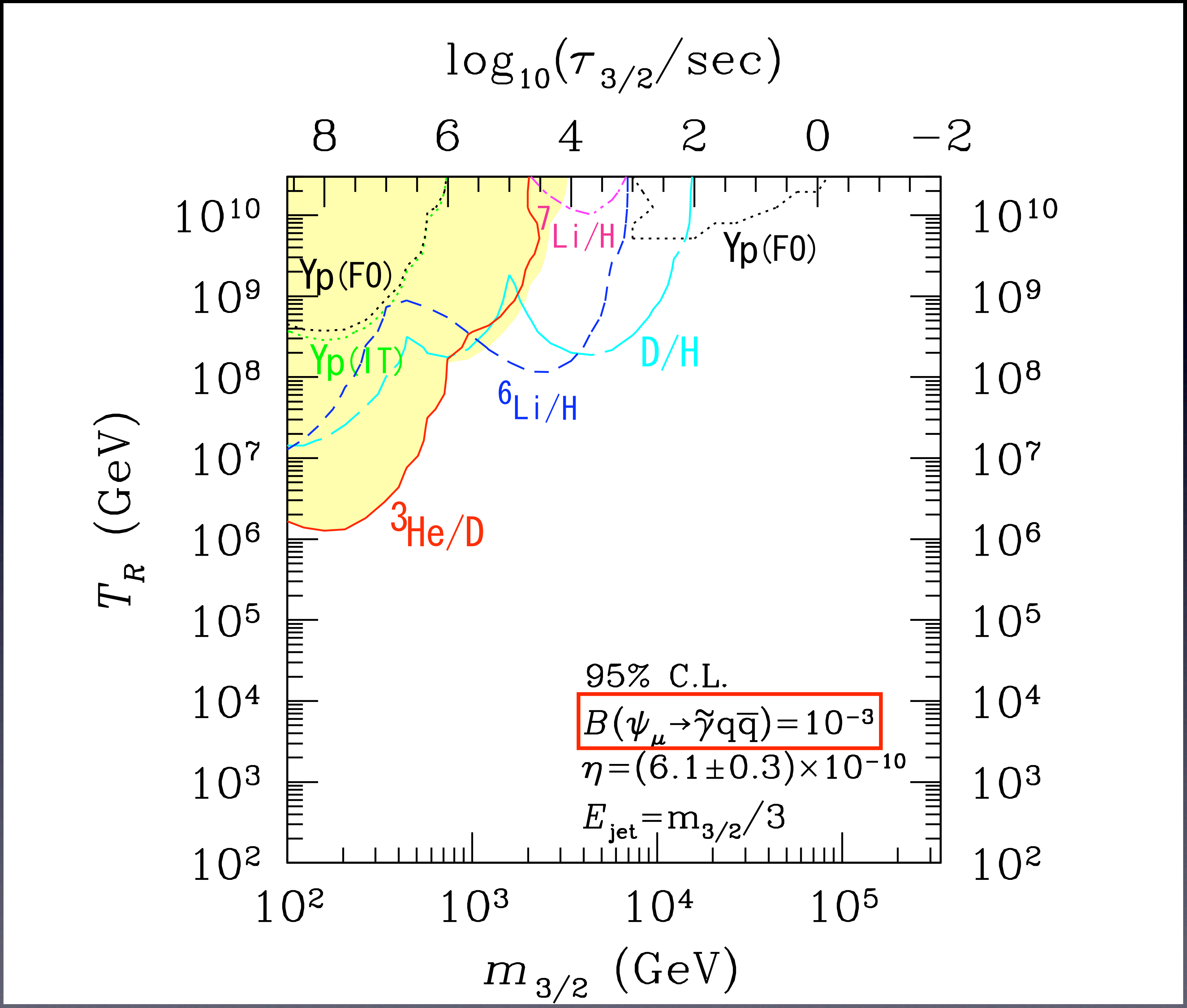
$$B_h \sim \alpha/4\pi \sim 0.001$$

quarks, gluons → energetic hadrons → hadro-dissociation → destruction & production of Light elements

Constraint on Reheating Temperature



Constraint on Reheating Temperature (2)



Non-thermal Gravitino Production

- Gravitinos are produced in the inflaton decay through supergravity effect

(1) pair production directly from inflaton

MK,F.Takahashi,Yanagida (2006)

$$\phi \longrightarrow \psi_{3/2} + \psi_{3/2}$$

(2) spontaneous decay into hidden quarks via Yukawa couplings

Endo,MK,F.Takahashi,Yanagida (2006)

$$\phi \longrightarrow \text{hidden quarks} \longrightarrow {\psi_{3/2}}'\text{s}$$

(3) anomaly-induced decay into hidden gauge sector

Endo,F.Takahashi,Yanagida (2007)

$$\phi \longrightarrow \text{hidden gauge sector} \longrightarrow {\psi_{3/2}}'\text{s}$$

- Production rate

$$\Gamma_{3/2} = \frac{\xi}{32\pi}\left(\frac{\langle\phi\rangle}{M_p}\right)^2 \frac{m_\phi^3}{M_p^2}$$

- SUSY breaking field $z, \quad m_z \sim \Lambda \sim (m_{3/2}M_p)^{1/2}$

dynamical SUSY beaking scale

a. For $m_\phi < m_z$

direct pair production (1) is effective $\xi \simeq 1$

b. For $m_\phi < m_z$

indirect production (2,3) is effective $\xi \sim 1/(8\pi^2)$

$$Y_{3/2}^{(NT)} = 2\frac{\Gamma_{3/2}}{\Gamma_\phi}\frac{3T_R}{4m_\phi}$$

$$\simeq 7\times 10^{-11}\xi\left(\frac{\langle\phi\rangle}{10^{15}\mathrm{GeV}}\right)^2\left(\frac{m_\phi}{10^{12}\mathrm{GeV}}\right)^3\left(\frac{T_R}{10^6\mathrm{GeV}}\right)^{-1}$$

Non-thermal vs. thermal

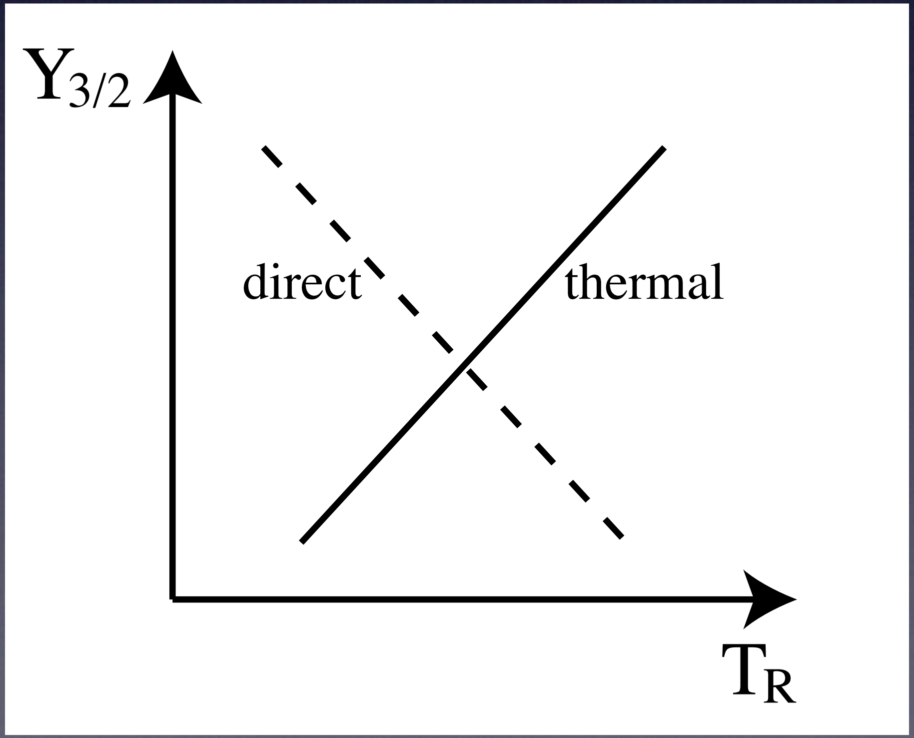
$$Y_{3/2}^{(NT)} \simeq 7 \times 10^{-11} \xi \left(\frac{\langle \phi \rangle}{10^{15}\text{GeV}} \right)^2 \left(\frac{m_\phi}{10^{12}\text{GeV}} \right)^3 \left(\frac{T_R}{10^6\text{GeV}} \right)^{-1}$$

$$Y_{3/2}^{(NT)} \propto T_R^{-1}$$

$$Y_{3/2}^{(TH)} \simeq 1.9 \times 10^{-12} \left[1 + \left(\frac{m_{g_3}^2}{3m_{3/2}^2} \right) \right] \left(\frac{T_R}{10^6\text{GeV}} \right)$$

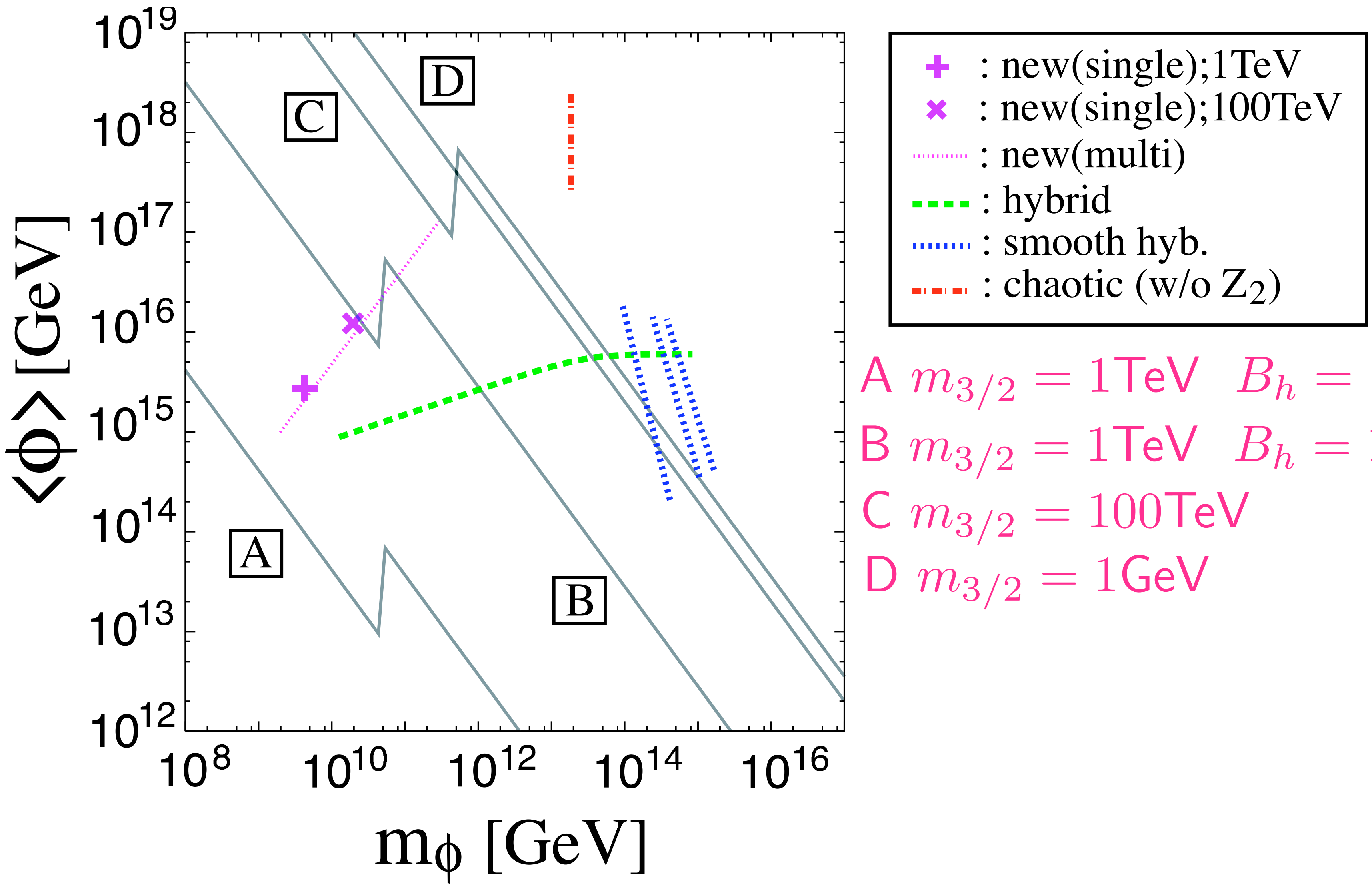
$$Y_{3/2}^{(TH)} \propto T_R$$

Non-thermal production is complementary to thermal production



Constraints on Inflation models

Endo,F.Takahashi,Yanagida (2007)



A $m_{3/2} = 1\text{TeV}$ $B_h = 1$

B $m_{3/2} = 1\text{TeV}$ $B_h = 10^{-3}$

C $m_{3/2} = 100\text{TeV}$

D $m_{3/2} = 1\text{GeV}$

set T_R the highest value allowed by cosmological constraints

Axion in SUSY

Axion and Strong CP Problem

QCD

$$\mathcal{L} = \mathcal{L}_{\theta=0} + \theta \frac{g^2}{32\pi^2} F^{a\mu\nu} \tilde{F}^a_{\mu\nu}$$

← ~~CP~~

Experiment → $\theta \lesssim 10^{-9}$

Why is θ so small? → strong CP problem

Solution to strong CP prob.

Peccei-Quinn Mechanism

$U(1)_{PQ}$ → ~~$U(1)_{PQ}$~~ at F_a : PQ scale

Nambu-Goldstone boson → AXION

Constraint on PQ scale

$$10^{10}\ \mathrm{GeV} \lesssim F_a \lesssim 10^{12}\ \mathrm{GeV}$$

Axion in SUSY

- Axion field forms supermultiplet

$$(\quad a(\text{axion}),\quad s(\text{saxion}),\quad \tilde{a}(\text{axino})\quad)$$

- Due to holomorphic property of superpotential real U(1) is extended to complex U(1)

  → Flat direction → saxion

- Saxion and axino lead to cosmological constraints

Saxion

- saxion gets a mass through SUSY breaking effects $m_s \simeq m_{3/2}$ (gravitino mass)
- Initial field value (after inflation)

$s_i \sim F_a$ $\quad$ $s_i - s(\text{vacuum}) \sim F_a$

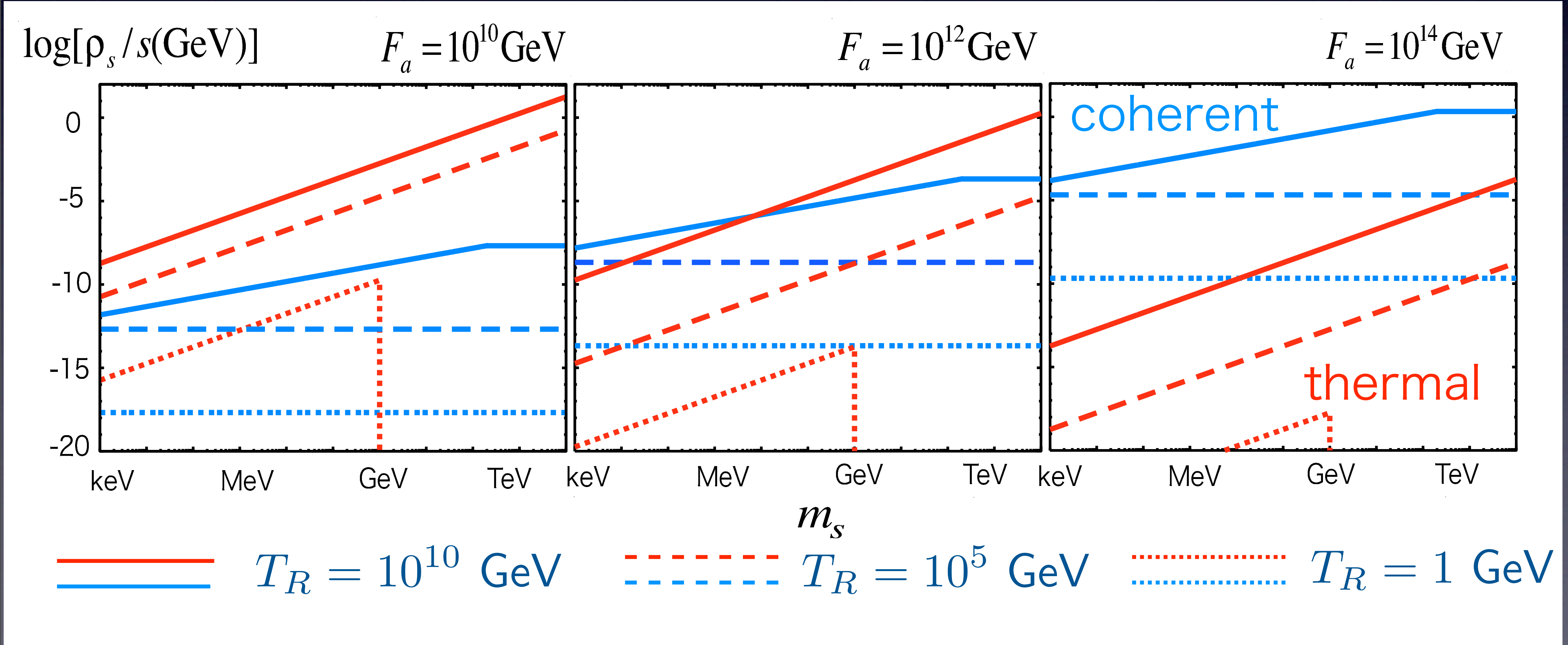
→ coherent oscillation of saxion when $H \simeq m_{3/2}$

$$\left(\frac{\rho_s}{s}\right)^{(\mathrm{C})} \simeq 2.1 \times 10^{-9}\ \mathrm{GeV} \left(\frac{T_R}{10^5\ \mathrm{GeV}}\right) \left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^2 \left(\frac{s_i}{F_a}\right)^2$$

for $m_s < \Gamma_I$

- Saxion is also produced by scatterings of particles in high temperature plasma

$$\left(\frac{\rho_s}{s}\right)^{(\mathrm{TP})} \sim 1.2\times10^{-9}\ \mathrm{GeV}\left(\frac{m_s}{1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^5\ \mathrm{GeV}}\right)\left(\frac{10^{12}\ \mathrm{GeV}}{F_a}\right)^2$$



Saxion Decay

- Deacy into two axions (model dep.) ← main decay if exist

$$\Gamma(s \to 2a) \simeq \frac{f^2}{64\pi}\frac{m_s^3}{F_a^2} \qquad f \sim O(1)$$

$$\tau \simeq 10^2\ \text{sec}\left(\frac{\text{GeV}}{m_s}\right)^3\left(\frac{F_a}{10^{12}\text{GeV}}\right)^2$$

- Decay into gluons, photons

$$\Gamma(s \to 2g) \simeq \frac{\alpha_s^2}{64\pi}\frac{m_s^3}{F_a^2} \qquad m_s > 1\ \text{GeV}$$

$$\Gamma(s \to 2\gamma) \simeq \frac{\kappa^2\alpha_{em}^2}{64\pi}\frac{m_s^3}{F_a^2} \qquad \kappa \sim O(1)$$

- Decay into quarks and leptons (DFSZ model)

$$\Gamma(s \to q\bar{q}, \ell\bar{\ell}) \sim \frac{3}{8\pi}\frac{m_{q,\ell}^2 m_s}{F_a^2}$$

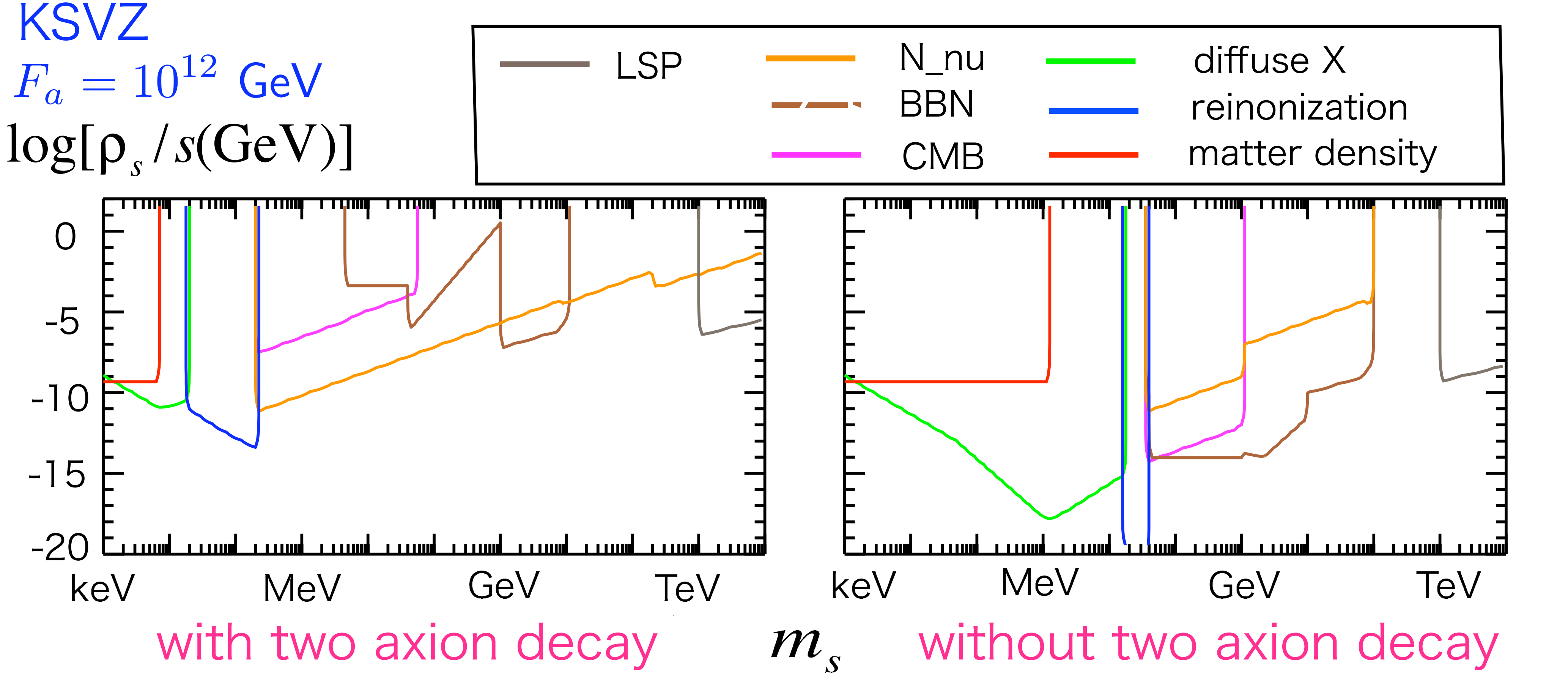
Cosmological Constraint

1. matter density $\tau_s > t_0$
2. increase of $N_{\nu\,\mathrm{eff}}$
3. affect BBN
4. CMB spectral distortion
5. reionization
6. diffuse X(γ)-rays
7. LSP overproduction

$m_s > m_{\mathrm{susy}} \sim 1$ TeV

KSVZ

$F_a = 10^{12}$ GeV



Axino and Constraints on T_R

- Axino is produced through scattering of particles in thermal bath

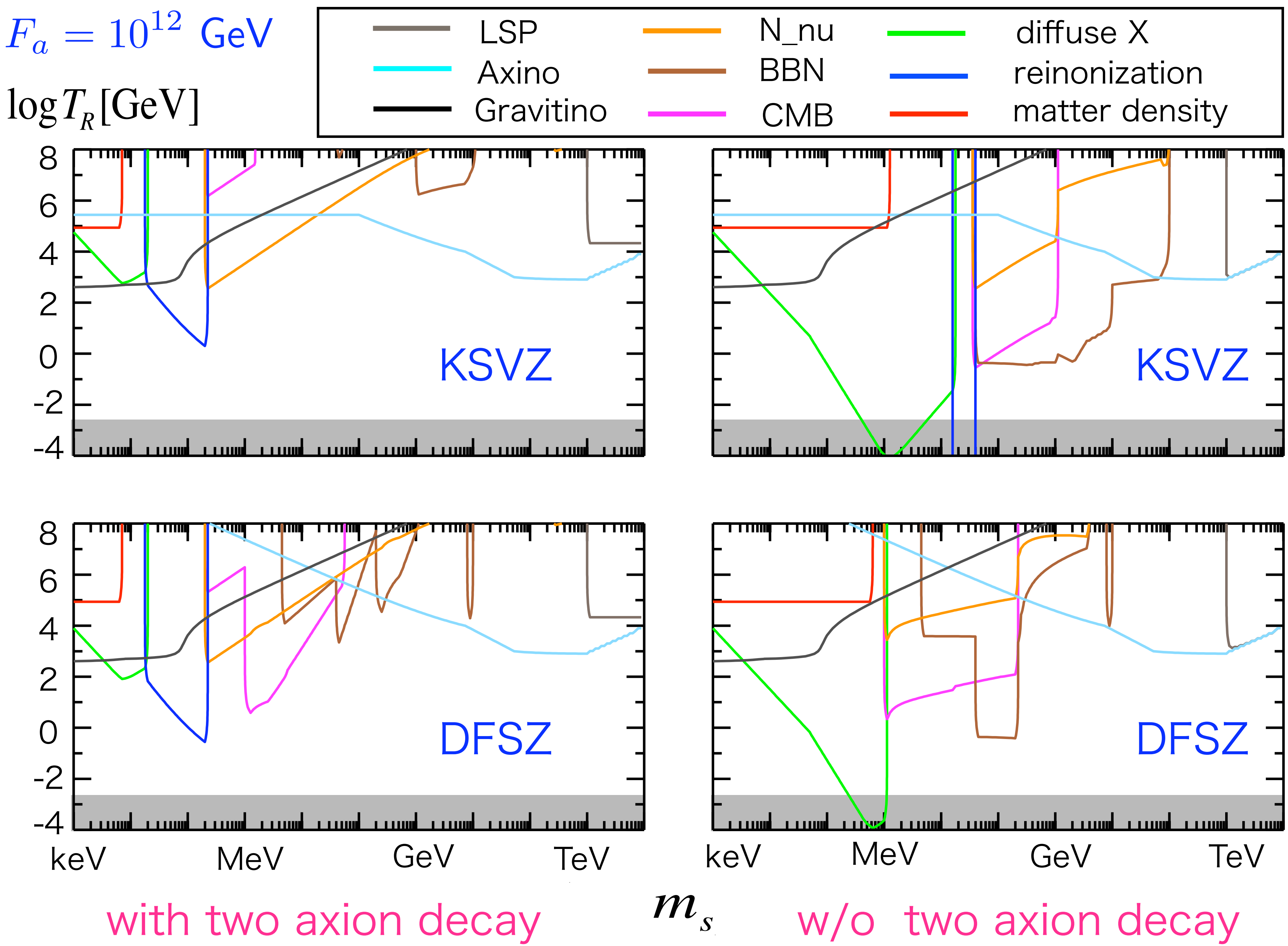
$$\frac{\rho_{\tilde{a}}}{s} \simeq 2 \times 10^{-7} g_s^6 \mathrm{GeV} \left(\frac{m_{\tilde{a}}}{1\mathrm{GeV}}\right) \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{-2} \left(\frac{T_R}{10^6\mathrm{GeV}}\right)$$

$$\rho_{\tilde{a}}/s \propto T_R$$

- Saxion density

$$\rho_s/s \propto T_R$$

→ Stringent Constraint on Reheating Temp.



$F_a = 10^{12}$ GeV
$\log T_R$[GeV]
LSP
Axino
Gravitino
N_nu
BBN
CMB
diffuse X
reinonization
matter density
KSVZ
KSVZ
DFSZ
DFSZ
8
6
4
2
0
-2
-4
keV
MeV
GeV
TeV
m_s
with two axion decay
w/o two axion decay

- Cosmological constraint on the reheating temperature is more stringent than that from gravitino

$$T_R \lesssim 10^5 \text{ GeV} \qquad m_s = m_{3/2} \lesssim 10 \text{ TeV}$$

→ Thermal leptogenesis does not work for $m_{3/2}$ < 10TeV

Summary

- Inflation is realized in the frame of supergravity
- SUGRA leads to inflaton decay and gives lower bound of reheating temperature
- Thermal and non-thermal production of gravitino, saxion and axino lead to stringent constraint on reheating temperature