Inflation in Gauge Mediation and Gravitino Dark Matter

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Y. N. and M. Sakai, Prog. Theor. Phys. 125 (2011) 395.

K. Kamada, Y. N. and M. Sakai, arXiv:1103.XXXX [hep-ph].

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1. Introduction

Inflation

Standard cosmologyの多くの問題を解決！

(flatness, horizon, monopole)

Inflatonの量子揺らぎ ➡ *構造形成, CMBの温度揺らぎ*

Inflation は、どのように particle physics の模型の中に埋め込まれるか？

Supersymmetry (SUSY)

標準模型を超える理論の有力な候補の一つ

Inflatonのflatなpotentialを自然に実現

SUSY は破れていなければならない

Gauge mediation

Hidden sectorの SUSY breakingを標準模型の
ゲージ相互作用でvisible sectorに伝える模型

Direct gauge mediation **K. I. Izawa, Y. Nomura, K. Tobe and T. Yanagida, Phys. Rev. D 56, 2886 (1997).**

SUSY breaking sectorの global symmetryを gauge 化 ⇒ *SM gauge symmetry*

Gaugino massが、しばしばscalar massに比べて小さくなる

<u>SUSY breaking vacuum の pseudomoduli space に tachyonic direction が存在</u>

⇒ *Sizable gaugino masses !* **Z. Komargodski and D. Shih, JHEP 0904, 093 (2009).**

(See also Y. N. and Y. Ookouchi, JHEP 1101, 093 (2011).)

Uplifted model

R. Kitano, H. Ooguri and Y. Ookouchi, Phys. Rev. D 75, 045022 (2007).

Lower vacuum が存在

⇒ *真空の安定性を保証する、２つの hierarchical mass scale ,* $m \gg \mu$

Higher vacuum は、cosmic history においてどのように選ばれたのか？

⇑

Inflation in the SUSY breaking sector !

m *: inflationary scale ,* μ *: SUSY breaking scale*

Inflation 後、Higher vacuum に落ちる

Inflaton と visible sector field との相互作用

(gauge mediation)

➡ *Reheating process が計算可能！*

Moduli oscillation and decay

(SUSY breaking)

➡ *Thermal bath で作られた gravitino を dilute ！*

Collider experiments, cosmological observations

(FCNC, dark matter abundance, BBN, ...)

➡ *Model parameter space に強い制限！*

Cosmic history in our scenario

SUSY breaking sector で inflation

↓ Moduli は原点に stabilize

Inflation終了

(Higher vacuum 付近に落ち込む)

↓

Inflaton decay

(Thermal bath で gravitino が大量生成)

↓ Moduli oscillation

Moduli domination

↓

Moduli decay

(Thermal bath で作られたGravitino は dilute,

Moduli decay による gravitino 生成)

↓

Big Bang Nucleosynthesis (BBN)

Gravitino dark matter

- *Thermal bath*
- *Moduli decay*

Contents

2. SUSY breaking

	$SU(N)$	$U(1)_1$	$U(1)_2$	$U(1)_R$
χ	$\mathbf{1}$	1	0	0
$\bar{\chi}$	$\mathbf{1}$	-1	0	0
ρ	$\square$	0	1	0
$\bar{\rho}$	$\bar{\square}$	0	-1	0
Z	$\square$	-1	1	2
$\bar{Z}$	$\bar{\square}$	1	-1	2
Y	$\mathbf{1}$	0	0	2
Φ	$\mathbf{1}$	0	0	2

Model

Wess-Zumino model
with $SU(N)$ global symmetry

$$W = m^2 Y + \mu^2 \Phi - h_{\rm Y} \chi Y \bar{\chi} - h_\Phi \rho \Phi \bar{\rho} - h_{\rm Z}(\chi Z \bar{\rho} + \rho \bar{Z} \bar{\chi}) - m_{\rm Z} Z \bar{Z}$$

$m \gg \mu$, $h_{\rm Y}, h_\Phi, h_{\rm Z}$: real coupling constants

SUSY breaking vacuum

$$Y = \rho = \bar{\rho} = Z = \bar{Z} = 0, \quad \chi = \bar{\chi} = \frac{m}{\sqrt{h_{\rm Y}}}$$

Φ : *pseudomoduli*

$\Rightarrow$ $V_0 = \mu^4$

Promoted to supergravity $\Rightarrow$ $\mu \simeq 7.9 \times 10^9\,\mathrm{GeV} \times \left(\frac{m_{3/2}}{15\,\mathrm{GeV}}\right)^{1/2}$

Mass spectrum

Pseudomoduli Φ は 1-loop で stabilize :

$$|\Phi_0| \simeq \frac{1}{2}\frac{m_Z}{h_\Phi}, \quad \arg \Phi_0 = 0,$$

$$m_\Phi^2 \simeq \frac{N}{64\pi^2}\frac{h_Y h_\Phi^4}{h_Z^2}\frac{\mu^4}{m^2} \equiv m_{CW}^2$$

	Fermions			Bosons		
	Weyl mult.	mass	$SU(N)$	Real mult.	mass	$SU(N)$
Φ	1	0	$\mathbf{1}$	2	$\mathcal{O}(m_{CW})$	$\mathbf{1}$
$Y,\ \chi,\ \bar{\chi}$	1	$\mathcal{O}(\sqrt{h_Y}m)$	$\mathbf{1}$	2	$\mathcal{O}(\sqrt{h_Y}m)$	$\mathbf{1}$
	1	$\mathcal{O}(\sqrt{h_Y}m)$	$\mathbf{1}$	2	$\mathcal{O}(\sqrt{h_Y}m)$	$\mathbf{1}$
	1	$g_V\frac{m}{\sqrt{h_Y}}$	$\mathbf{1}$	2	$g_V\frac{m}{\sqrt{h_Y}}$	$\mathbf{1}$
$Z,\ \bar{Z},\ \rho,\ \bar{\rho}$	$2N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\square+\bar{\square}$	$4N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\square+\bar{\square}$
	$2N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\square+\bar{\square}$	$4N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\square+\bar{\square}$

Vacuum stability

SUSY vacuum が存在 : $\chi\bar{\chi} = \frac{m^2}{h_Y}, \quad \rho\bar{\rho} = \frac{\mu^2}{h_\Phi}, \quad \Phi = \frac{h_Z^2}{h_Y h_\Phi}\frac{m^2}{m_Z}, \cdots$

SUSY breaking vacuum は metastable Decay rate : $\Gamma_{vac} \propto e^{-S}, \quad S \sim \left(\frac{m}{\mu}\right)^4$

Mass hierarchy : $m \gg \mu$

Gauge mediation

$SU(N)$ global symmetry ⇨ *standard model gauge symmetry*

$Z,\ \bar{Z},\ \rho,\ \bar{\rho}$: *messengers*

⇨
$$\begin{cases} m_{\lambda_i} \simeq \dfrac{g_i^2}{16\pi^2}\dfrac{h_{\rm Y}h_\Phi}{h_{\rm Z}^2}\dfrac{\mu^2}{m}\dfrac{m_{\rm Z}}{m}, \\ m_{\tilde{f}}^2 \simeq \sum_i C_2^i \left(\dfrac{g_i^2}{16\pi^2}\right)^2 \dfrac{h_{\rm Y}h_\Phi^2}{h_{\rm Z}^2}\dfrac{\mu^4}{m^2} \end{cases}$$

$g_i\ (i = 1, 2, 3)$: $U(1) \times SU(2) \times SU(3)$ standard model gauge coupling

C_2^i : quadratic Casmir

Gaugino-to-scalar mass ratio : $r_{\rm g} \equiv m_{\tilde{g}}/m_{\tilde{e}}$

Sizable gaugino mass ⇦ *Lower vacuumが存在*

Z. Komargodski and D. Shih, JHEP 0904, 093 (2009).

3. Inflationary scenario

Hybrid inflation in the SUSY breaking sector

Y : *inflaton* , $\chi, \bar{\chi}$: *waterfall fields* $(\rho = \bar{\rho} = Z = \bar{Z} = \Phi = 0)$

Inflation 中の Hubble induced mass で stabilize

$$V_{\rm g} \simeq e^{|\psi|^2/M_{\rm Pl}^2}(3H^2 M_{\rm Pl}^2) \simeq 3H^2|\psi|^2 + \cdots$$

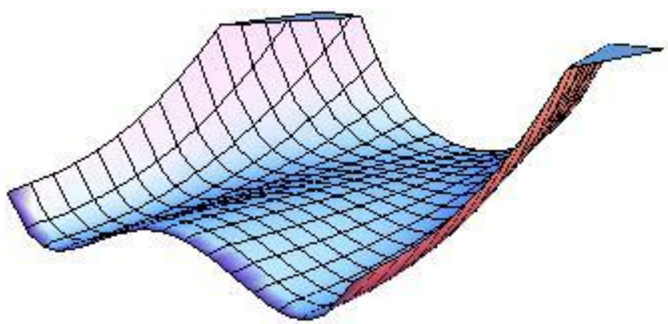
$$\Rightarrow \quad V_{\rm tree} \simeq \left|m^2 - h_{\rm Y}\chi\bar{\chi}\right|^2 + h_{\rm Y}^2|Y|^2(|\chi|^2 + |\bar{\chi}|^2)$$

$|Y| > Y_c \equiv m/\sqrt{h_{\rm Y}}$ $\quad \chi = \bar{\chi} = 0$ $\Rightarrow$ *Inflation !* $\quad H \simeq \sqrt{\frac{1}{3}}\frac{m^2}{M_{\rm Pl}}$

$|Y| < Y_c$ $\quad \chi = \bar{\chi} = \frac{m}{\sqrt{h_{\rm Y}}}$

Inflaton motion

Loop correction



Cosmological perturbation

COBE/WMAP normalization, $\mathcal{P}_{\mathcal{R}}^{1/2} \simeq 4.9 \times 10^{-5}$

$$\Rightarrow \quad \frac{m}{h_{\rm Y}^{1/2}} \simeq 5.9 \times 10^{15}{\rm GeV} \times \begin{cases} \left(\dfrac{h_Y}{3\times 10^{-3}}\right)^{1/3} & \text{for} \quad h_Y < 3\times 10^{-3} \\ \left(\dfrac{\mathcal{N}_{\rm COBE}}{51}\right)^{-1/4} & \text{for} \quad h_Y > 3\times 10^{-3} \end{cases}$$

Spectral tilt :

$$n_s = 1 - 6\epsilon + 2\eta \simeq \begin{cases} 1 - \dfrac{h_{\rm Y}^3 M_{\rm pl}^2}{2\pi^2 m^2} \simeq 1 & \text{for} \quad h_Y < 3\times 10^{-3} \\ 1 - \dfrac{1}{\mathcal{N}_{\rm COBE}} \simeq 0.98, & \text{for} \quad h_Y > 3\times 10^{-3} \end{cases}$$

Scalar-to-tensor ratio :

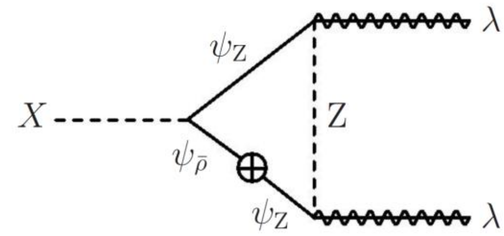
$$r = 16\epsilon \simeq \begin{cases} \dfrac{h_{\rm Y}^{10/3}}{16\pi^4}\left(\dfrac{h_{\rm Y}^{5/6} M_{\rm pl}}{m}\right)^2 & \text{for} \quad h_Y < 3\times 10^{-3} \\ \dfrac{h_{\rm Y}^2}{2\pi^2}\dfrac{1}{\mathcal{N}_{\rm COBE}} & \text{for} \quad h_Y > 3\times 10^{-3} \end{cases}$$

以下、$h_Y < 3 \times 10^{-3}$

Reheating after inflation

Inflaton と waterfall field $X \equiv \chi + \bar{\chi}$ の decay

$\mathcal{O}(\sqrt{h_{\rm Y}} m)$ mass



MSSM gaugino pair に dominant に decay

(messenger への decay は禁止 , $2h_Z > h_Y$)

$$T_{\rm R} \simeq \left(\frac{90}{\pi^2 g_*^{\rm R}}\right)^{1/4} \times \sqrt{\Gamma_{\rm R} M_{\rm Pl}}$$

$$\simeq 0.45 \times \frac{N^2}{(4\pi)^2} \left(\frac{\sqrt{h_{\rm Y}}}{8\pi}\right)^{1/2} \frac{h_{\rm Y}^4 g_3^2}{h_{\rm Z}^3} (m M_{\rm Pl})^{1/2}$$

$g_*^{\rm R} \simeq 220$

<u>Thermal bath で gravitino が生成</u>

M. Kawasaki, K. Kohri and T. Moroi, Phys. Lett. B 625, 7 (2005); Phys. Rev. D 71, 083502 (2005).

$$\frac{\rho_{3/2}^{\rm (th)}}{s} \simeq 9.5 \times 10^{-8}\,{\rm GeV} \times \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^2 \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right)^{-1} \left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right)$$

s : entropy density

overproduced ! $\frac{\rho_{3/2}}{s} < \frac{\rho_{\rm DM}}{s} \simeq 4.1 \times 10^{-10}\,{\rm GeV}$

4. Gravitino dark matter

Moduli oscillation

Inflation 中、moduli は原点に stabilize

$H < m_\Phi$ ➡ Φ_0 *周りで振動開始 (radiation dominated era)*

$$T_{\rm osc} \simeq \left(\frac{90}{\pi^2 g_*^{\rm osc}} \right)^{1/4} \times \sqrt{M_{\rm Pl} m_\Phi}$$

$$\simeq 1.2 \times 10^{10}\,{\rm GeV} \times \left(\frac{m_\Phi}{300\,{\rm GeV}} \right)^{1/2} \qquad g_*^{\rm osc} \simeq 220$$

Moduli の長い lifetime ➡ *宇宙の energy density を dominate*

➡ *Thermally produced gravitino を dilute*

$$\Delta^{-1} \simeq \frac{T_{\rm d}}{T_{\rm osc}} \left(\frac{|\Phi_0|}{\sqrt{3} M_{\rm Pl}} \right)^{-2}$$

$T_{\rm d}$: moduli decay temperature

$$|\Phi_0| \simeq 1.1 \times 10^{14}\,{\rm GeV} \times \left(\frac{r_{\rm g}}{3.5} \right)^2 \left(\frac{m_{3/2}}{15\,{\rm GeV}} \right) \left(\frac{m_{\tilde g}}{1.5\,{\rm TeV}} \right)^{-1}$$

振動の安定性 ➡ $r_{\rm g} \lesssim 4.5$

Moduli decay

M. Ibe and R. Kitano, Phys. Rev. D75, 055003 (2007). (See also M. Endo and F. Takahashi, arXiv:0710.1561 [hep-ph];
K. Hamaguchi, R. Kitano, F. Takahashi, JHEP 0909, 127 (2009).)

Dominant decay process : $\Phi \to hh \quad (m_\Phi > 2m_h)$

Interaction Lagrangian :
$$\mathcal{L}_{\tilde{f}} = \frac{\partial m_{\tilde{f}}^2(\Phi)}{\partial \Phi} \Phi \tilde{f} \tilde{f}^\dagger + \mathrm{h.c.}$$
$$\simeq \frac{3}{4} \sum_i C_2^i \left(\frac{g_i^2}{16\pi^2} \right)^2 \frac{h_\mathrm{Y}^2 h_\Phi^3}{h_\mathrm{Z}^4} \frac{\mu^4 m_\mathrm{Z}}{m^4} \Phi \tilde{f} \tilde{f}^\dagger + \mathrm{h.c.}$$

$$T_\mathrm{d} \simeq \sqrt{\Gamma_\mathrm{H} M_\mathrm{Pl}}$$
$$\simeq 4.4\,\mathrm{MeV} \times \left(\frac{r_\mathrm{g}}{3.5} \right)^{-2} \left(\frac{m_{\tilde{g}}}{1.5\,\mathrm{TeV}} \right)^3 \left(\frac{m_{3/2}}{15\,\mathrm{GeV}} \right)^{-1} \left(\frac{m_\Phi}{300\,\mathrm{GeV}} \right)^{-1/2}$$

Γ_H : decay width

Gravitino abundance

Moduli decay : $\Phi \to \psi_{3/2}\psi_{3/2}$ (longitudinal mode)

Interaction Lagrangian : $\mathcal{L}_{3/2} \simeq -\frac{N}{(16\pi)^2}\frac{h_{\rm Y}h_\Phi^4}{h_{\rm Z}^2}\left(\frac{\mu}{m}\right)^2 \Phi^\dagger \bar{\psi}_{3/2}\psi_{3/2} + c.c.$

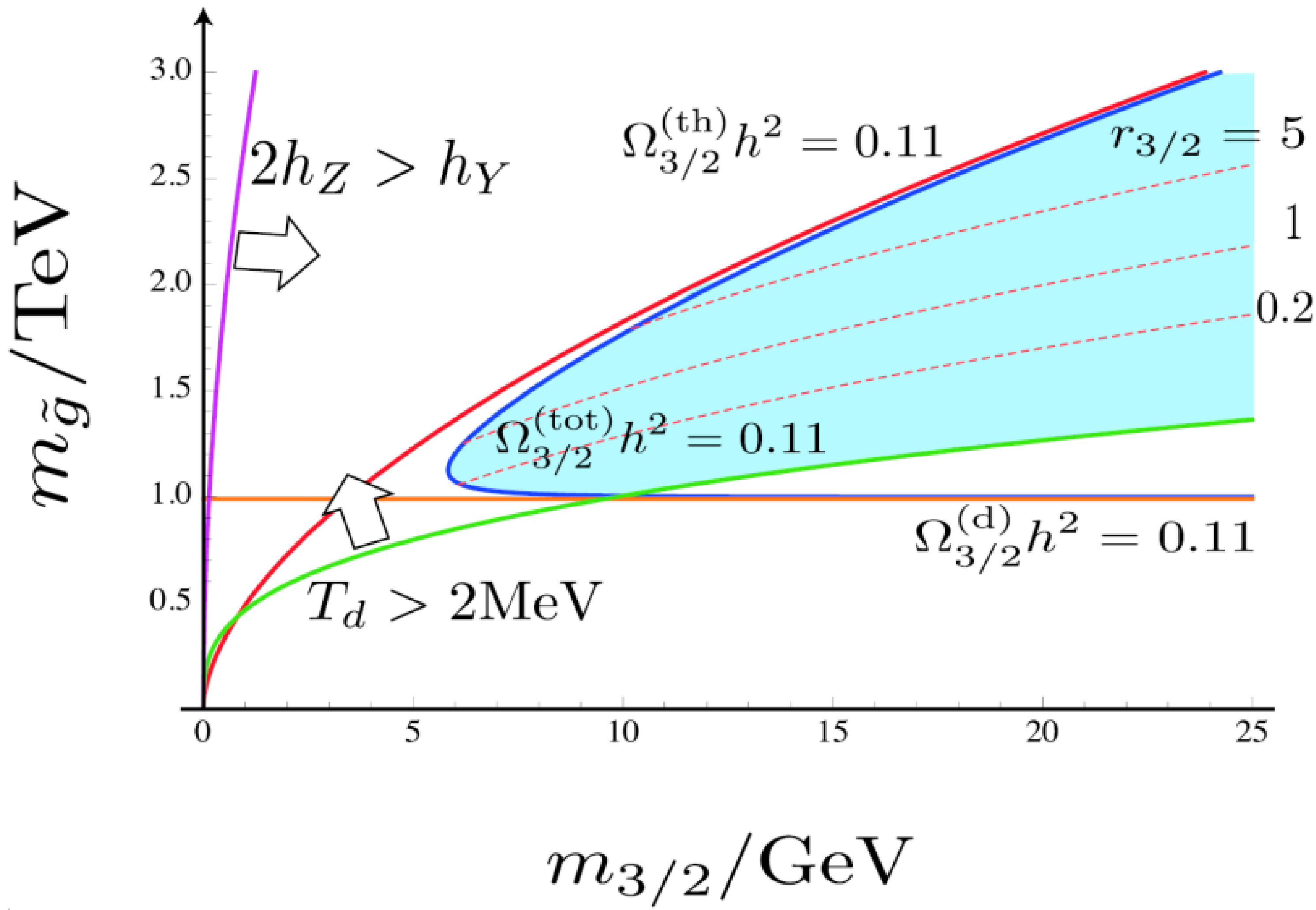
➡ Gravitino number density : $\frac{n_{3/2}}{s} = \frac{3}{4}\frac{T_{\rm d}}{m_\Phi} B_{3/2} \times 2$ $\quad B_{3/2} \equiv \Gamma_{3/2}/\Gamma_H$

➡ Density parameter : $\Omega_{3/2}^{(\rm d)} h^2 \simeq 0.033 \times \left(\frac{r_{\rm g}}{3.5}\right)^2 \left(\frac{m_\Phi}{300\,{\rm GeV}}\right)^{9/2} \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^{-3}$

Gravitino abundance produced in thermal bath $(T_{\rm R} \simeq T_{\rm osc})$

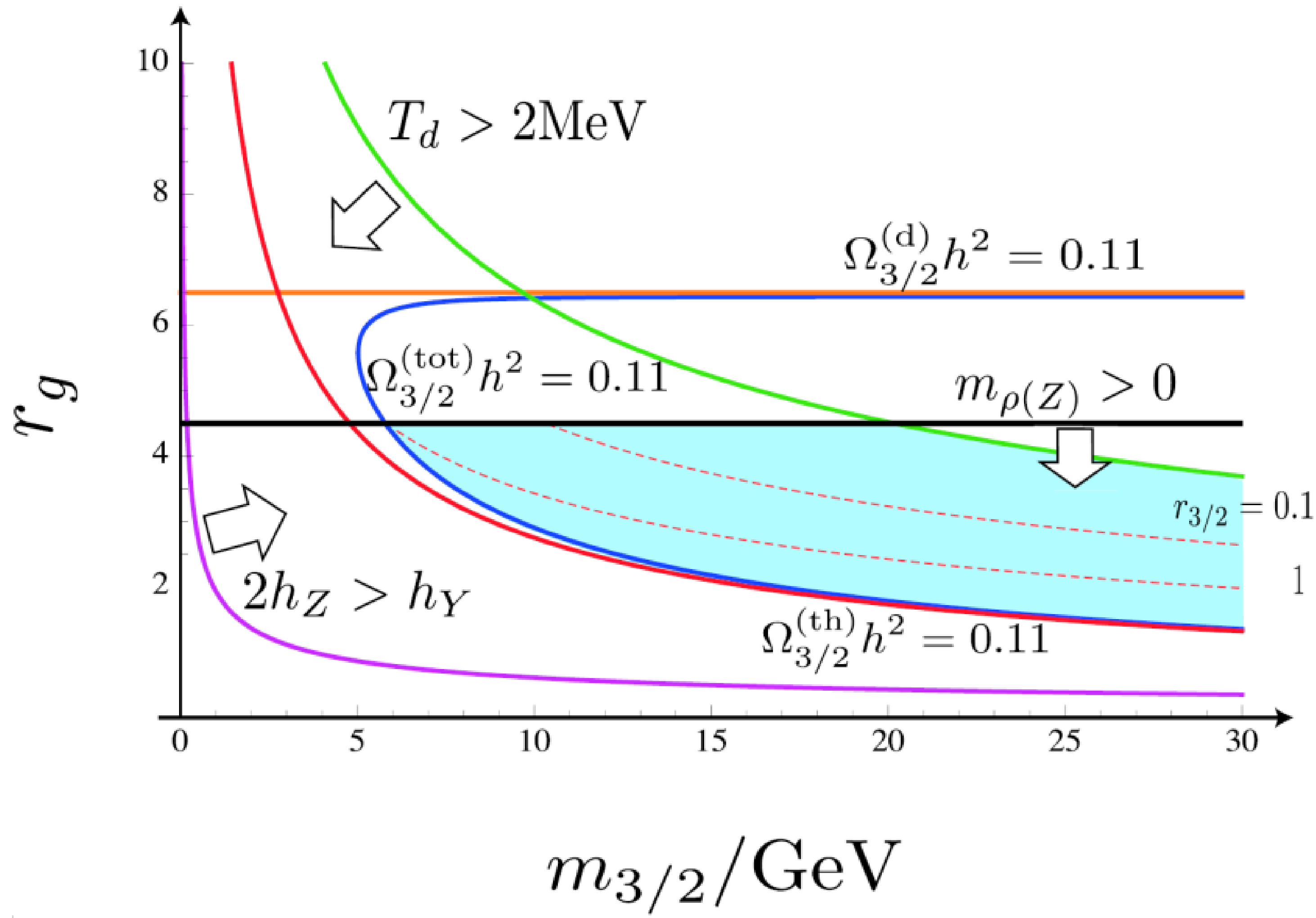
Dilution factor Δ^{-1}

➡ $\Omega_{3/2}^{(\rm th)} h^2 \simeq 0.016 \times \left(\frac{r_{\rm g}}{3.5}\right)^{-6} \left(\frac{m_\Phi}{300\,{\rm GeV}}\right)^{-1/2} \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^7 \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right)^{-4}$



Moduli mass : $300\ \mathrm{GeV}$, $r_{\mathrm{g}} = 3.5$

$r_{3/2} \equiv \Omega^{(\mathrm{th})}_{3/2}/\Omega^{(\mathrm{d})}_{3/2}$



Moduli mass : $300\,\mathrm{GeV}$, Gluino mass : $1.5\,\mathrm{TeV}$

5. Summary

Inflation in the SUSY breaking sector and gauge mediation

Inflation 後、metastable vacuum が自然に選ばれる

Reheating process ⇐ Messenger loop

Moduli oscillation & decay

⇒ [Thermal bath で大量生成された gravitino を dilute

Non-thermally produced gravitino]

⇒ ***Gravitino dark matter***

Model parameter に強い制限

Future work

Baryogenesis

Dilution factor $\Delta^{-1} \simeq 10^{-3}$

⇨ Moduli domination の前に十分な baryon asymmetry

SUSY breaking sector と関係した baryogenesis ?

様々なinflation模型

Cosmic string problem

他の inflation model で置き換えられる？

Model parameters

$$h_\Phi \simeq 0.036 \times \frac{1}{\sqrt{N}} \left(\frac{r_{\rm g}}{3.5}\right) \left(\frac{m_\Phi}{300\,{\rm GeV}}\right) \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^{-1}$$

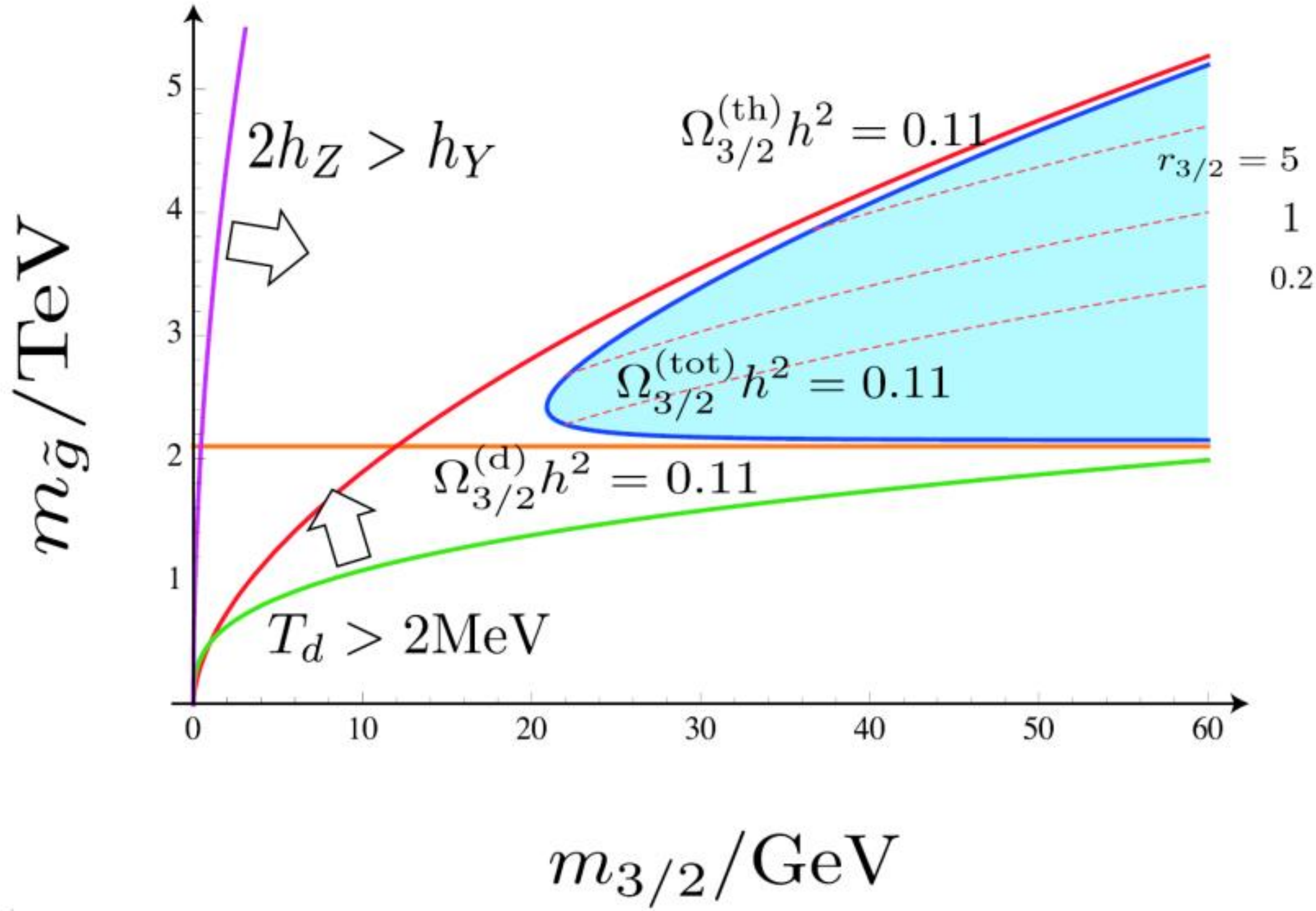
$$h_{\rm Z} \simeq 1.8 \times 10^{-3} \times \frac{1}{\sqrt{N}} \left(\frac{r_{\rm g}}{3.5}\right)^2 \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right) \left(\frac{m_\Phi}{300\,{\rm GeV}}\right) \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^{-2} \left(\frac{h_Y}{3 \times 10^{-3}}\right)^{-1/3}$$

$$h_{\rm Y} \simeq 2.2 \times 10^{-3} \times \frac{1}{N^{21/34}} \times \left(\frac{r_{\rm g}}{3.5}\right)^{18/17} \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right)^{9/17} \left(\frac{m_\Phi}{300\,{\rm GeV}}\right)^{21/34} \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^{-18/17}$$

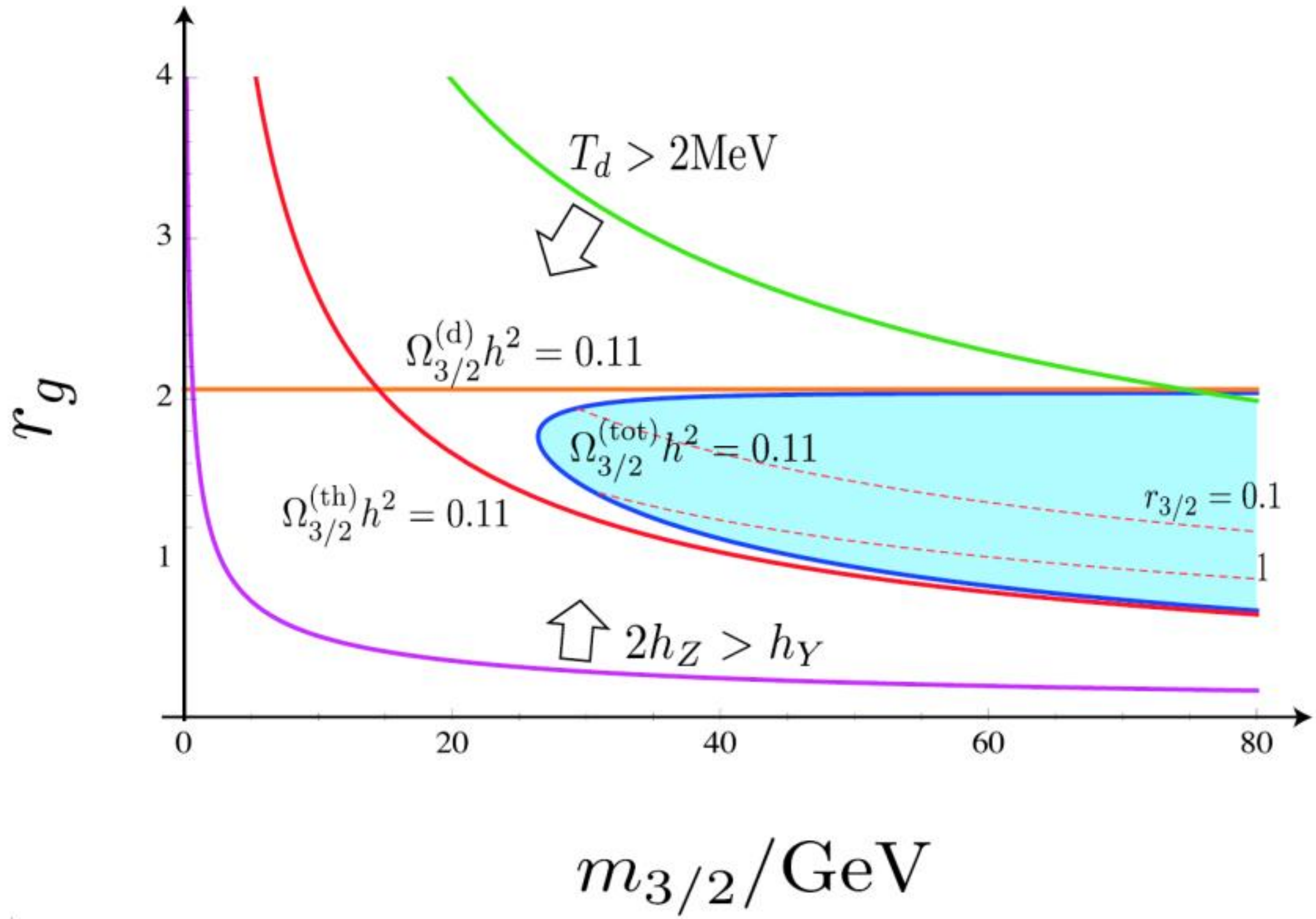
$$\mu \simeq 7.9 \times 10^9\,{\rm GeV} \times \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right)^{1/2}$$

$$\frac{m}{h_{\rm Y}^{1/2}} \simeq 5.9 \times 10^{15} {\rm GeV} \times \begin{cases} \left(\dfrac{h_Y}{3 \times 10^{-3}}\right)^{1/3} & \text{for} \quad h_Y < 3 \times 10^{-3} \\ \left(\dfrac{\mathcal{N}_{\rm COBE}}{51}\right)^{-1/4} & \text{for} \quad h_Y > 3 \times 10^{-3} \end{cases}$$

$$m_{\rm Z} \simeq 8.2 \times 10^{12}\,{\rm GeV} \times \frac{1}{\sqrt{N}} \left(\frac{r_{\rm g}}{3.5}\right)^3 \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right) \left(\frac{m_\Phi}{300\,{\rm GeV}}\right) \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^{-2}$$



Moduli mass : $500\,\mathrm{GeV}$, $r_{\mathrm{g}} = 3.5$



Moduli mass : $500\,\mathrm{GeV}$, Gluino mass : $1.5\,\mathrm{TeV}$