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, Prog. Theor. Phys. 126 (2011) 35.

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1. Introduction

Supersymmetry (SUSY)

is one of the most promising candidates beyond the standard model.

However, …

SUSY must be broken.

The allowed region of soft SUSY breaking parameters is very severely constrained.

For example, FCNC requires …

squark masses : $(m_Q^2)_{ij} = m_Q^2 \delta_{ij} + (\Delta m_Q^2)_{ij}$ ⇨ $\Delta m^2 \ll m^2$

Moreover, …

It is difficult to break SUSY spontaneously in the visible sector.

(Due to the existence of a light superpartner.)

Then, we take the following scenario …

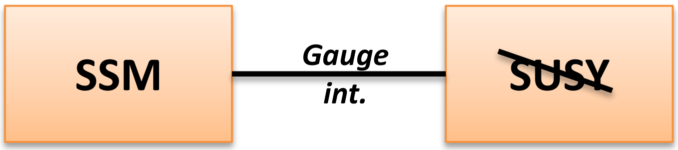
SUSY breaking in the hidden sector is transmitted into the visible sector by some interactions.

<u>Gauge mediation</u>

transmits the SUSY breaking in the hidden sector to the visible sector by <u>the standard model gauge interactions</u>.

⇧

Flavor blind ⇨ FCNC is naturally suppressed !



The soft mass spectrum in gauge mediation

C. Cheung, A. L. Fitzpatrick and D. Shih, JHEP 0807, 054 (2008).

$$W = \mathcal{M}_{ij}(X)\phi_i\widetilde{\phi}_j = (\lambda_{ij}X + m_{ij})\phi_i\widetilde{\phi}_j$$

$\phi_i,\ \widetilde{\phi}_i$ ($i,\ j = 1, \ldots, N$) : messengers , $\mathbf{5} \oplus \overline{\mathbf{5}}$ under $SU(5) \supset G_{\rm SM}$

$\langle X \rangle = X + \theta^2 F,$

Gaugino mass : $M_r = \dfrac{\alpha_r}{4\pi}\Lambda_G, \qquad \Lambda_G = F\,\partial_X \log\det\mathcal{M}$

Scalar mass :

$$m^2_{\widetilde{f}} = 2\sum_{r=1}^{3} C_{\widetilde{f}}^{\ r}\left(\frac{\alpha_r}{4\pi}\right)^2\Lambda_S^2, \qquad \Lambda_S^2 = \frac{1}{2}|F|^2\frac{\partial^2}{\partial X\partial X^*}\sum_{i=1}^{N}\left(\log|\mathcal{M}_i|^2\right)^2$$

$\mathcal{M}_i$: eigenvalues of $\mathcal{M}$

Gravitino mass in gauge mediation

Promoted to supergravity ⇨ $$m_{3/2} = \frac{F}{\sqrt{3}M_{pl}}$$

$\sqrt{F} \gtrsim 100\,\mathrm{TeV}$ ⇨ $m_{3/2} \gtrsim 10\,\mathrm{eV}$

⇨ *Gravitino LSP !* *(Usually, a bino or stau is NLSP.)*

> Gravitino can be a candidate of the dark matter.

But, we must worry about the gravitino problem …

Considering spontaneous SUSY breaking in the hidden sector ,
we will see a connection between …

Vacuum structure in the hidden sector $\Leftrightarrow$ Gaugino mass

Obtaining sizable gaugino masses is closely related with the structure of the SUSY breaking vacuum.

We will then consider a possibility which realizes …

- Cosmological inflation
- Gauge mediation
- Gravitino dark matter with the correct abundance

<u>in just one SUSY breaking model !</u>

Contents

2. Gaugino mass and landscape of vacua

Case 1

$W = X_0(f + \lambda\varphi_1\varphi_2) + m(X_1\varphi_1 + X_2\varphi_2)$ *with canonical Kahler potential*

X_0 : SUSY breaking field , $\varphi_1, \varphi_2, X_1, X_2$: messengers

SUSY breaking vacuum :

$\langle X_1 \rangle = \langle X_2 \rangle = \langle \varphi_1 \rangle = \langle \varphi_2 \rangle = 0$

$\langle X_0 \rangle$ *: pseudomoduli field* (tree-level flat direction)

It always exists in the case with canonical Kahler potential.

Gaugino mass: $m_{\tilde{g}} \sim f \dfrac{\partial}{\partial X} \log\det \mathcal{M}_F$

$\mathcal{M}_F$: fermion mass matrix of messengers , $\det \mathcal{M}_F = -m^2$

⇨ $m_{\tilde{g}} \simeq 0$ *Vanishing leading order gaugino mass !*

Direct gauge mediation

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

The global symmetry in the SUSY breaking sector is weakly gauged. ⇨ *SM gauge symmetry*

Gaugino mass is often smaller than scalar mass.

⇨ *When we take gaugino mass the 1TeV order, scalar mass typically becomes very heavy.*

⇨ *The hierarchy problem occurs again !*

Why does the leading order gaugino mass vanish ?

How can we take it nonzero ?

Case 2

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

$$W = \lambda X(\phi_1\tilde{\phi}_1 + \phi_2\tilde{\phi}_2) + m\phi_1\tilde{\phi}_2 + fX$$ *with canonical Kahler potential*

X : SUSY breaking field , $\phi_1, \tilde{\phi}_1, \phi_2, \tilde{\phi}_2$: messengers

Metastable SUSY breaking vacuum :

$$\langle\phi_1\rangle = \langle\tilde{\phi}_1\rangle = \langle\phi_2\rangle = \langle\tilde{\phi}_2\rangle = 0$$

$\langle X \rangle$ *: pseudomoduli field* (tree-level flat direction)

Gaugino mass: $m_{\tilde{g}} \sim f\dfrac{\partial}{\partial X}\log\det\mathcal{M}_F$

$\mathcal{M}_F$: fermion mass matrix of messengers , $\det\mathcal{M}_F = \lambda^2 X^2$

⇒ $m_{\tilde{g}} \sim \dfrac{f}{\langle X \rangle}$ *Nonzero leading order gaugino mass !*

$\langle X \rangle = 0$ in pseudomoduli space

➡ Eigenvalues of scalar mass matrix : $\left(m^2 \pm \sqrt{m^4 + 4\lambda^2 f^2}\right)/2$

⬆ *Tachyonic !!*

In fact, SUSY vacuum exists. ($X = 0,\ \phi,\ \tilde{\phi} \neq 0$)

The leading order gaugino mass is nonzero only when there is a tachyonic direction in the pseudomoduli space of the SUSY breaking vacuum.

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

Intuitive understanding

Nonzero leading order gaugino mass ➡ $\det \mathcal{M}_F$ *is a function of X.*

For example, $\mathcal{M}_F = \lambda X + m$ ➡ *Zero point exists.* $\left(X = -\dfrac{m}{\lambda}\right)$

SUSY breaking mass splitting : $\pm F$ ➡ *Tachyonic direction appears at zero point !*

A model with non-canonical Kahler potential

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

There is no pseudomoduli in general.

If there is a pseudomoduli space …

Sizable gaugino mass can be obtained without tachyonic direction !

If there is no pseudomoduli space …

How is the relation between gaugino mass and vacuum stability ?

⇨ Leading order gaugino mass can be nonzero on the global minimum !

Cf. **Y. Nomura, K. Tobe and T. Yanagida, Phys. Lett. B 425, 107 (1998).**

Return to the canonical case …

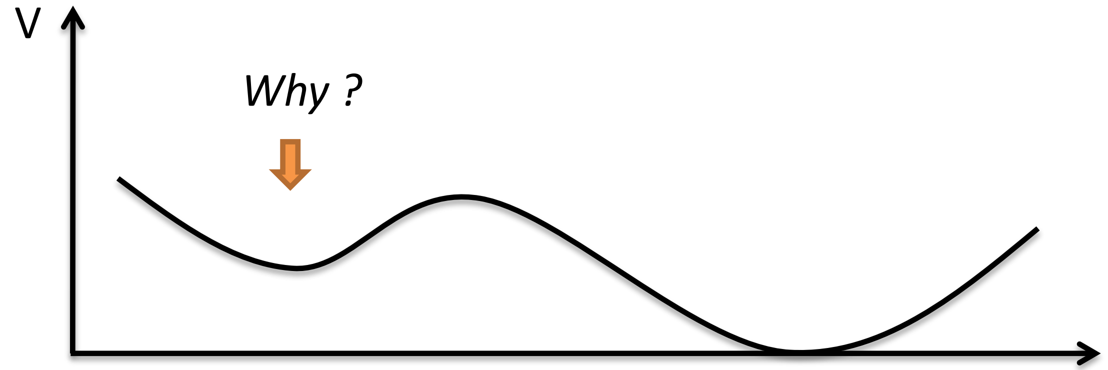
Is such a vacuum stable ?

If messengers are not tachyonic at the stabilized point, …

⇨ The vacuum is metastable.

However, when we consider cosmology …

Why the higher vacuum is selected in the cosmic history ?



3. Inflation in gauge mediation

Inflation

A period of very rapid expansion of the universe.

⇧

It solves many problems in standard cosmology !

(flatness, horizon, monopole)

Quantum fluctuations of the inflaton can set the initial condition of structure formation.

⇨ Inflation is now considered as the standard scenario of the early universe.

Then, a natural question is …

How is inflation embedded in a particle physics model ?

We here consider a possibility of …

Inflation in the SUSY breaking sector of gauge mediation

SUSY breaking sector field is identified as the inflaton.

Higher vacuum is naturally selected after inflation.

The inflaton interacts with the visible sector fields through the messengers in gauge mediation.

⇨ *Reheating process is calculable and predictable !*

The SUSY breaking vacuum has a pseudomoduli.

⇨ *Moduli oscillation and decay dilute gravitinos produced in the thermal bath !*

Cosmic history in our scenario

Inflation in the SUSY breaking sector

⇩ Moduli stabilizes at the origin.

Inflation ends.

⇩

Inflaton decay

Many gravitinos are produced in the thermal bath.

⇩ Moduli oscillation

Moduli domination

⇩

Moduli decay

Gravitinos are diluted.

Gravitinos are also produced by the decay process.

⇩

Big Bang Nucleosynthesis (BBN)

Gravitino dark matter

Thermal bath

Moduli decay

Before we see a concrete realization of our scenario , …

<u>Caution !</u>

Our model is **the first step** toward a viable SUSY breaking model with inflation.

Some observables may be already inconsistent with experiments.

Our model has some unattractive properties.

(Baryogenesis, …)

We leave these problems to the future study …

Model

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

Kahler potential is canonical.

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

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

$m \gg \mu$, $h_{\rm Y}, h_\Phi, h_{\rm Z}$: 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*

⇨ $V_0 = \mu^4$

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

Mass spectrum

Pseudomoduli Φ is stabilized at 1-loop :

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

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

	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	$g_V \frac{m}{\sqrt{h_Y}}$	$\mathbf{1}$
$Z,\ \bar{Z},\ \rho,\ \bar{\rho}$	$2N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\Box + \bar{\Box}$	$4N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\Box + \bar{\Box}$
	$2N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\Box + \bar{\Box}$	$4N$	$\mathcal{O}(\frac{h_Z}{\sqrt{h_Y}}m)$	$\Box + \bar{\Box}$

Vacuum stability

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

SUSY breaking vacuum is 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*

⇒
$$\begin{cases} m_{\lambda_i} \simeq \dfrac{g_i^2}{16\pi^2} \dfrac{h_\Upsilon h_\Phi}{h_Z^2} \dfrac{\mu^2}{m} \dfrac{m_Z}{m}, \\ m_{\tilde{f}}^2 \simeq \sum_i C_2^i \left(\dfrac{g_i^2}{16\pi^2} \right)^2 \dfrac{h_\Upsilon h_\Phi^2}{h_Z^2} \dfrac{\mu^4}{m^2} \end{cases}$$

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

C_2^i : quadratic Casmir

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

Sizable gaugino mass ⇐ *The existence of the lower vacuum*

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

Inflationary scenario

Hybrid inflation in the SUSY breaking sector

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

↑

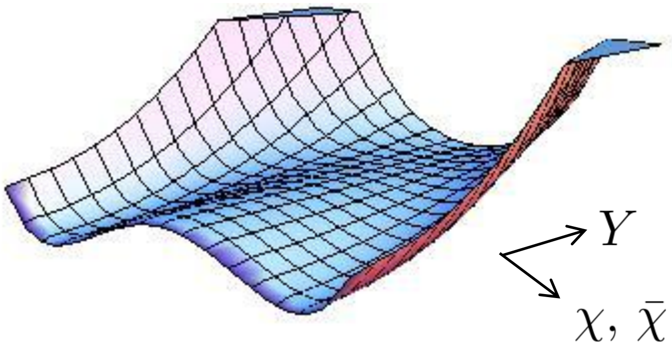
stabilized by Hubble induced mass during inflation.

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

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

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

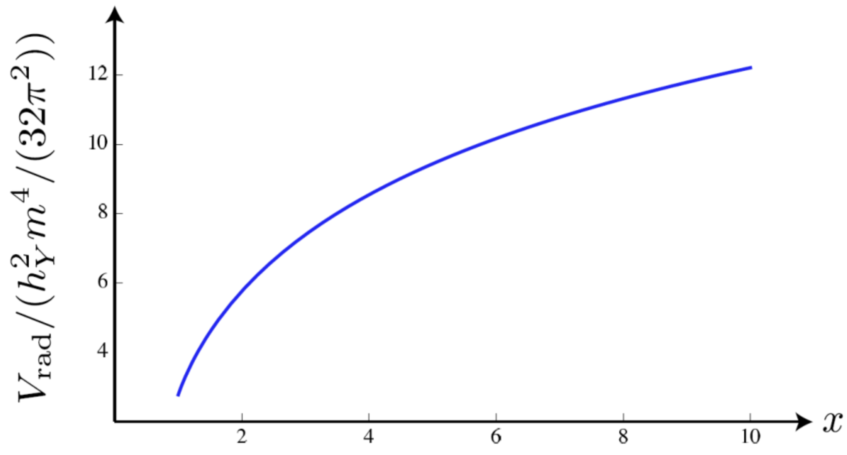
$|Y| < Y_c$ $\quad \chi = \bar{\chi} = \frac{m}{\sqrt{h_{\rm Y}}}$



Inflaton motion

Loop correction due to the waterfall fields

➡ *The flat inflaton potential is lifted.*

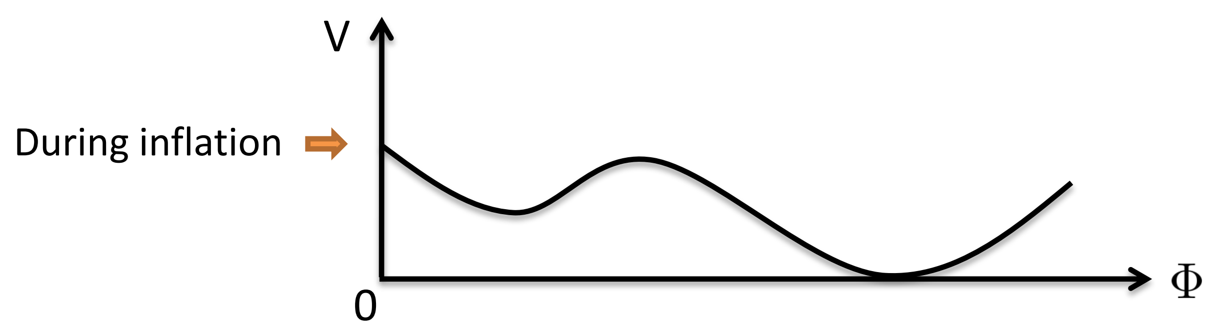


$(x \equiv Y/Y_c)$

The inflaton rolls off to the critical point. ➡ *Inflation ends.*

Moduli stabilizes at the origin during inflation by the Hubble effect.

➡ Metastable vacuum is naturally selected after inflation !



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 :

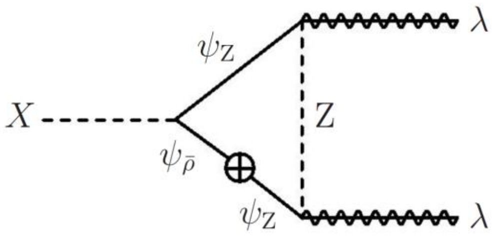
$$r = 16\epsilon \simeq \begin{cases} \dfrac{h_{\rm Y}^{10/3}}{16\pi^4} \left(\dfrac{h_{\rm Y}^{5/6} M_{\rm pl}}{m}\right)^2 & \text{for} \quad h_Y < 3 \times 10^{-3} \\ \dfrac{h_{\rm Y}^2}{2\pi^2} \dfrac{1}{\mathcal{N}_{\rm COBE}} & \text{for} \quad h_Y > 3 \times 10^{-3} \end{cases}$$

Hereafter , $h_Y < 3 \times 10^{-3}$

Reheating after inflation

The decays of the inflaton
and the waterfall field $X \equiv \chi + \bar{\chi}$

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



They dominantly decay into an SSM gaugino pair.

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

$$\simeq 0.45 \times \frac{N^2}{(4\pi)^2}\left(\frac{\sqrt{h_{\rm Y}}}{8\pi}\right)^{1/2} \frac{h_{\rm Y}^4 g_3^2}{h_{\rm Z}^3} (m M_{\rm Pl})^{1/2} \qquad g_*^{\rm R} \simeq 220$$

<u>Gravitinos are produced in the thermal bath.</u>

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

s : entropy density

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

Moduli oscillation

Moduli stabilizes at the origin during inflation by the Hubble effect.

⟺ Moduli stabilizes with a nonzero vev on the SUSY breaking vacuum.

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

$H < m_\Phi$ ⇒ The oscillation starts around Φ_0

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

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

There is a tachyonic direction in the pseudomoduli space.

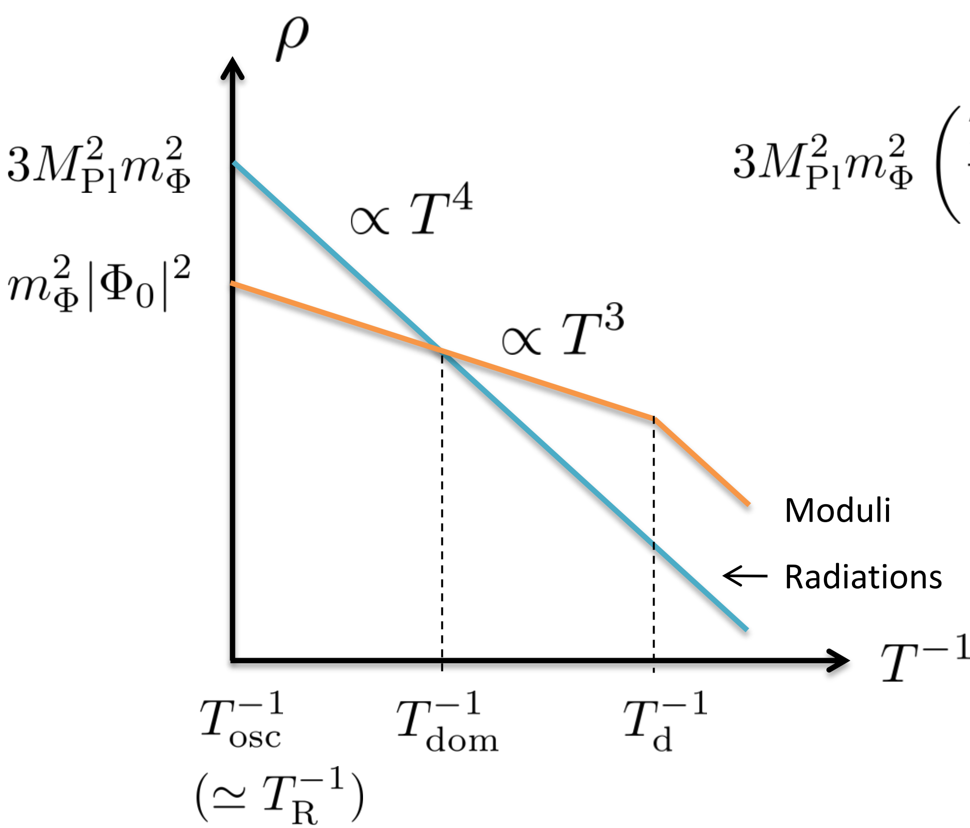
The stability of oscillation ⇒ $r_{\mathrm{g}} \lesssim 4.5$

Entropy production

The long lifetime of moduli ➡ *The oscillation dominates the energy density of the universe.*

The decay of moduli ➡ *Entropy production*

➡ *Thermally produced gravitinos are diluted.*



$$3M_{\rm Pl}^2 m_\Phi^2 \left(\frac{T_{\rm dom}}{T_{\rm osc}}\right)^4 = m_\Phi^2|\Phi_0|^2 \left(\frac{T_{\rm dom}}{T_{\rm osc}}\right)^3$$

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

➡ Dilution factor :

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

Moduli decay

M. Ibe and R. Kitano, Phys. Rev. D75, 055003 (2007) , … (many other works)

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

Interaction Lagrangian : $\mathcal{L}_{\tilde{f}} = \dfrac{\partial m_{\tilde{f}}^2(\Phi)}{\partial \Phi} \Phi \tilde{f} \tilde{f}^\dagger + \mathrm{h.c.}$

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

$$T_\mathrm{d} \simeq \sqrt{\Gamma_\mathrm{H} M_\mathrm{Pl}}$$

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

Γ_H : decay width

The temperature is required to be above ~2 MeV so that the BBN properly occurs.

Gravitino abundance

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

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

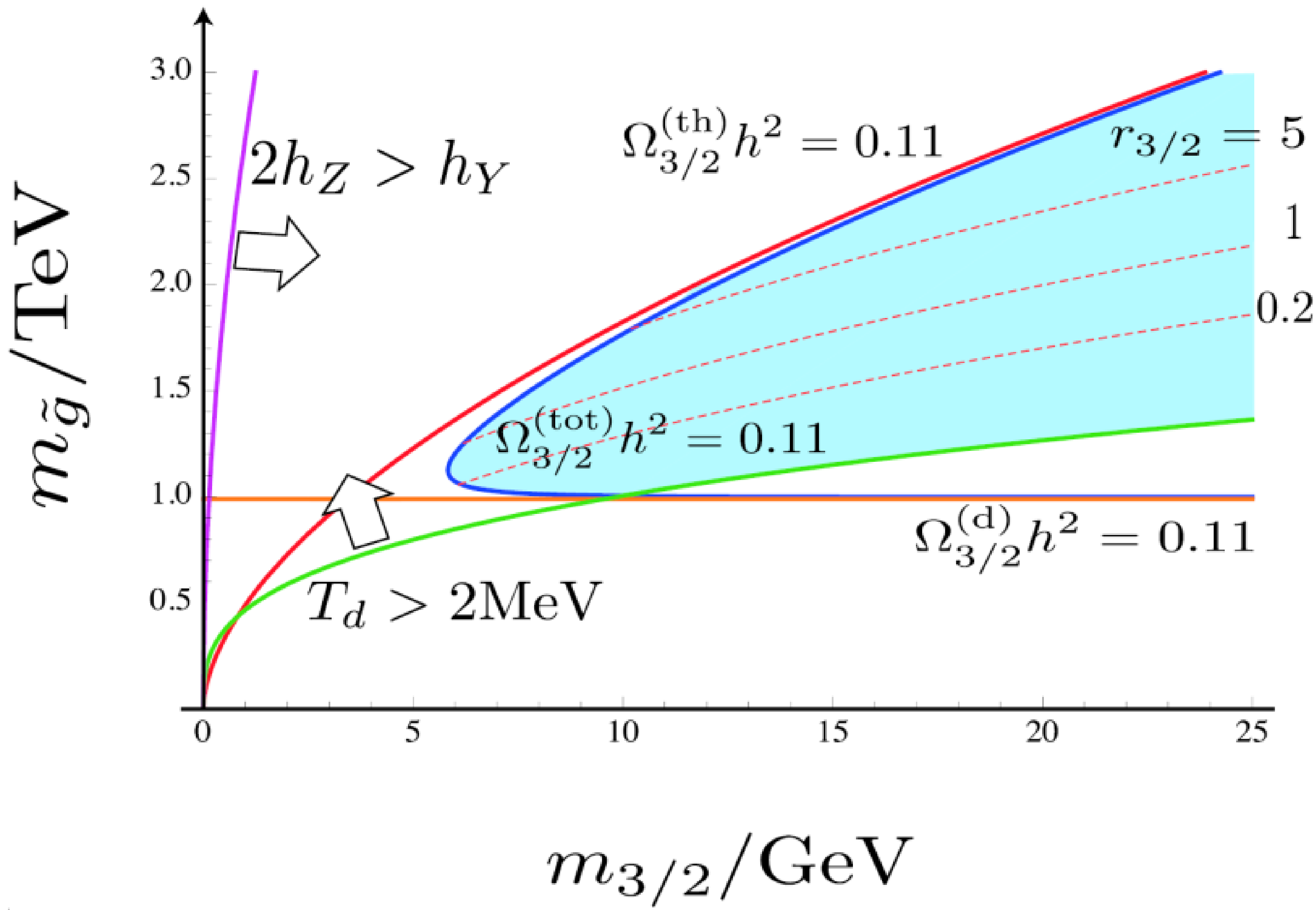
➡ Gravitino number density : $\frac{n_{3/2}}{s} = \frac{3}{4}\frac{T_d}{m_\Phi}B_{3/2} \times 2$ $\qquad B_{3/2} \equiv \Gamma_{3/2}/\Gamma_H$

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

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

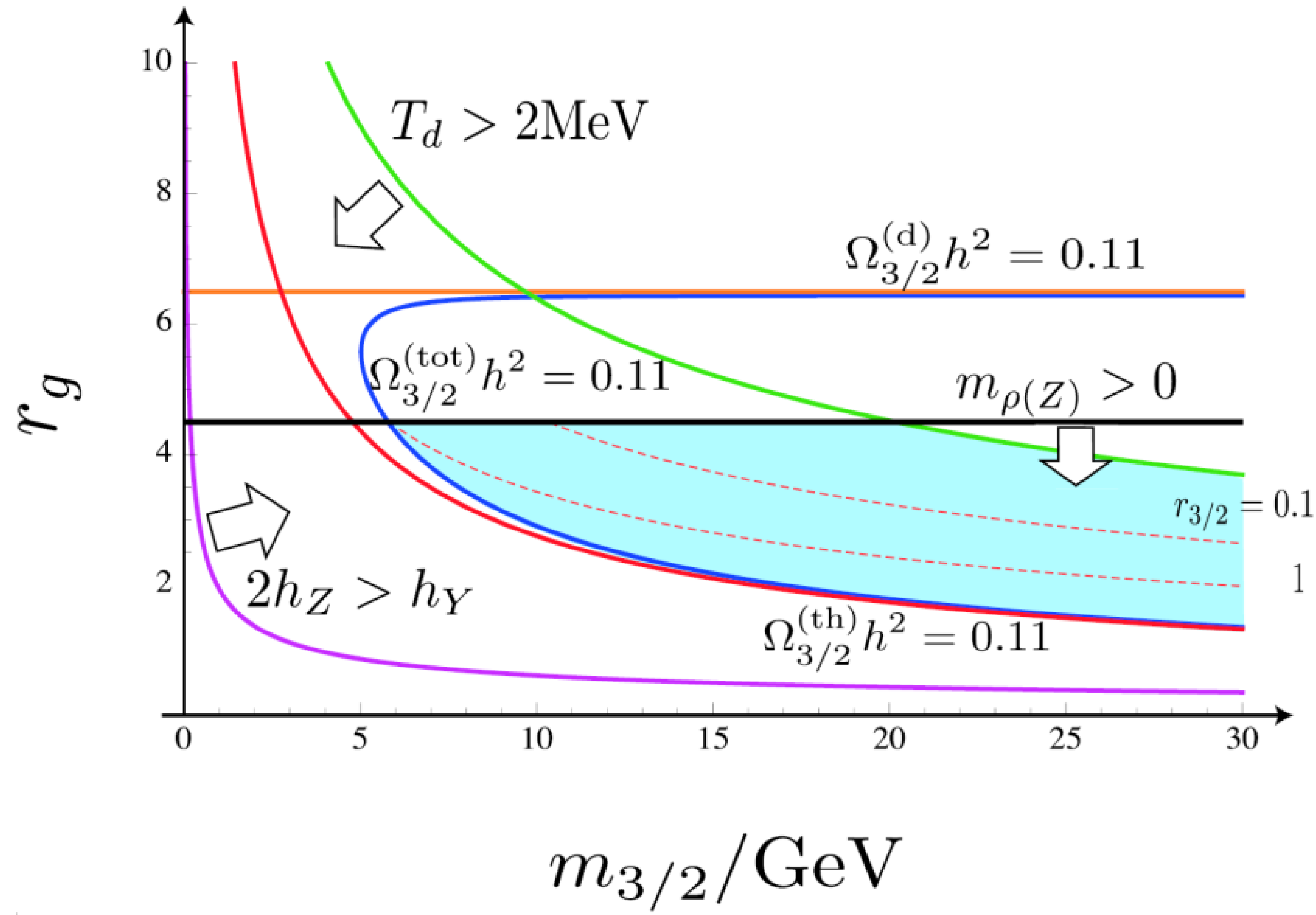
Dilution factor Δ^{-1}

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



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

Model parameters

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

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

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

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

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

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

4. Summary

Inflation in the SUSY breaking sector of gauge mediation

Metastable vacuum is naturally selected after inflation.

Reheating process ⇐ Messenger loop

Moduli oscillation & decay

⇒ [Thermally produced gravitinos are diluted.
Non-thermally produced gravitino

⇒ ***Gravitino dark matter***

Model parameters are severely constrained.

Future work

Baryogenesis

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

⇨ Sufficient baryon asymmetry is required before moduli domination.

Various inflation models

Cosmic string problem ,

η problem ,

Small coupling constants , ...

Thank you for your attention !

Extra slides

1-loop lifting of pseudomoduli

1-loop effective potential (Coleman-Weinberg potential) :

$$
\begin{aligned}
V_{eff}^{(1)} &= \frac{1}{64\pi^2} \mathrm{STr} \left(\mathcal{M}^4 \log \frac{\mathcal{M}^2}{M_{cutoff}^2} \right) \\
&\equiv \frac{1}{64\pi^2} \left[\mathrm{Tr} \left(m_B^4 \log \frac{m_B^2}{M_{cutoff}^2} \right) - \mathrm{Tr} \left(m_F^4 \log \frac{m_F^2}{M_{cutoff}^2} \right) \right]
\end{aligned}
$$

m_B^2, m_F^2 : tree-level boson and fermion masses (functions of pseudomoduli vev)

M_{cutoff} : UV cutoff

Φ^a : k chiral superfields , $K = \Phi^a \overline{\Phi}^a$, $W(\Phi^a)$

$$
\Rightarrow \quad m_0^2 = \begin{pmatrix} \overline{W}^{ac} W_{cb} & \overline{W}^{abc} W_c \\ W_{abc} \overline{W}^c & W_{ac} \overline{W}^{cb} \end{pmatrix} , \qquad m_{1/2}^2 = \begin{pmatrix} \overline{W}^{ac} W_{cb} & 0 \\ 0 & W_{ac} \overline{W}^{cb} \end{pmatrix}
$$

$W_c \equiv \partial W / \partial Q^c$, m_0^2 , $m_{1/2}^2$: $2k \times 2k$ matrix

More general case

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

$$W = \mathcal{M}_F(X)_{ab}\tilde{\phi}^a\phi^b + f(X)$$ *with non-canonical Kahler potential*

X : SUSY breaking field , $\phi, \tilde{\phi}$: messengers , $\mathcal{M}_F$: messenger mass matrix

There is no pseudomoduli in general.

Preserving the flat direction of X

➡ $$\partial_X g^{X\bar{X}}\big|_0 = 0$$

⮤ $\langle\phi^a\rangle = \langle\tilde{\phi}^a\rangle = 0$

$$g_{a\bar{a}} = \partial_a\partial_{\bar{a}}K$$

$$\mathcal{L}_{scalar} = g_{a\bar{a}}\partial_\mu\Phi^a\partial^\mu\bar{\Phi}^{\bar{a}} - V(\Phi,\bar{\Phi}) \ , \qquad V = g^{a\bar{a}}\partial_a W\partial_{\bar{a}}\bar{W}$$

A model with non-canonical Kahler potential

$$W = \lambda X(\phi_1\tilde{\phi}_1 + \phi_2\tilde{\phi}_2) + m\phi_1\tilde{\phi}_2 + fX$$

$$K = |X|^2 + \left(1 + \frac{|X|^2}{M^2}\right)\left(|\phi_1|^2 + |\tilde{\phi}_2|^2\right) + \left(1 - \frac{|X|^2}{M^2}\right)\left(|\tilde{\phi}_1|^2 + |\phi_2|^2\right)$$

M : cut-off scale

$\partial_X g^{X\bar{X}}\big|_0 = 0$ ⇨ *The flat direction of* X

Canonical Kahler potential ⇨ *A tachyonic direction around* $\langle X \rangle = 0$

Now … The eigenvalues of messenger boson mass-squared matrix :

$$\frac{1}{2}\left(m^2 \pm \sqrt{m^4 + 4\,\lambda^2 f^2 - 4\,(f/M)^2 m^2 + 4\,(f/M)^4}\right)$$

$\lambda^2 f^2 - (f/M)^2 m^2 + (f/M)^4 < 0$ ⇨ Sizable gaugino mass without tachyonic direction !

Sizable gaugino mass on the global minimum

If there is no pseudomoduli space …

How is the relation between gaugino mass and vacuum stability ?

⇨ Leading order gaugino mass can be nonzero on the global minimum !

Y. Nomura, K. Tobe and T. Yanagida, Phys. Lett. B 425, 107 (1998).

Example **(SUSY breaking sector + Messenger sector + Visible sector)**

SUSY breaking sector : $U(1)$ gauge theory ⇦ *Messenger gauge interaction*

$$W = X_0(f + \lambda\varphi_1\varphi_2) + m(X_1\varphi_1 + X_2\varphi_2)\ , \qquad f \ll m^2$$

U(1) charge of $X_0,\ X_1,\ X_2,\ \varphi_1$ and φ_2 : $0,\ -1,\ 1,\ 1$ and -1

SUSY breaking vacuum : $\langle X_1\rangle = \langle X_2\rangle = \langle\varphi_1\rangle = \langle\varphi_2\rangle = 0$

X_0 has a nonzero F-term.

Messenger sector : $W_{mess} = y_q S q \tilde{q} + y_E S E \tilde{E} + \frac{\kappa}{3} S^3$

q and $\tilde{q}$: messengers , $S, \underline{E, \tilde{E}}$: standard model gauge singlet

↑

U(1) charge : $1, -1$

Integrating out the SUSY breaking sector

$$\Rightarrow \quad m_E^2 = m_{\tilde{E}}^2 \sim \left(\frac{g_{mess}^2}{16\pi^2}\right)^2 \left(\frac{\lambda f}{m}\right)^2$$

g_{mess} : U(1) gauge coupling

⇒ 1-loop effect of $E, \tilde{E}$ ⇒ Negative mass of S : $-m_S^2 \simeq \frac{4}{16\pi^2} y_E^2 m_E^2 \ln \frac{\Lambda}{m_E}$

Λ : Cut-off scale

$y_E \lesssim 1 \Rightarrow m_E^2 \gg |m_S^2|$

- Effective scalar potential of the messenger sector :

$$V_{mess} = \left|y_E S\tilde{E}\right|^2 + \left|y_E S E\right|^2 + \left|y_q S\tilde{q}\right|^2 + \left|y_q S q\right|^2 + \left|y_E E\tilde{E} + y_q q\tilde{q} + \kappa S^2\right|^2 + m_E^2|E|^2 + m_E^2|\tilde{E}|^2 + m_S^2|S|^2.$$

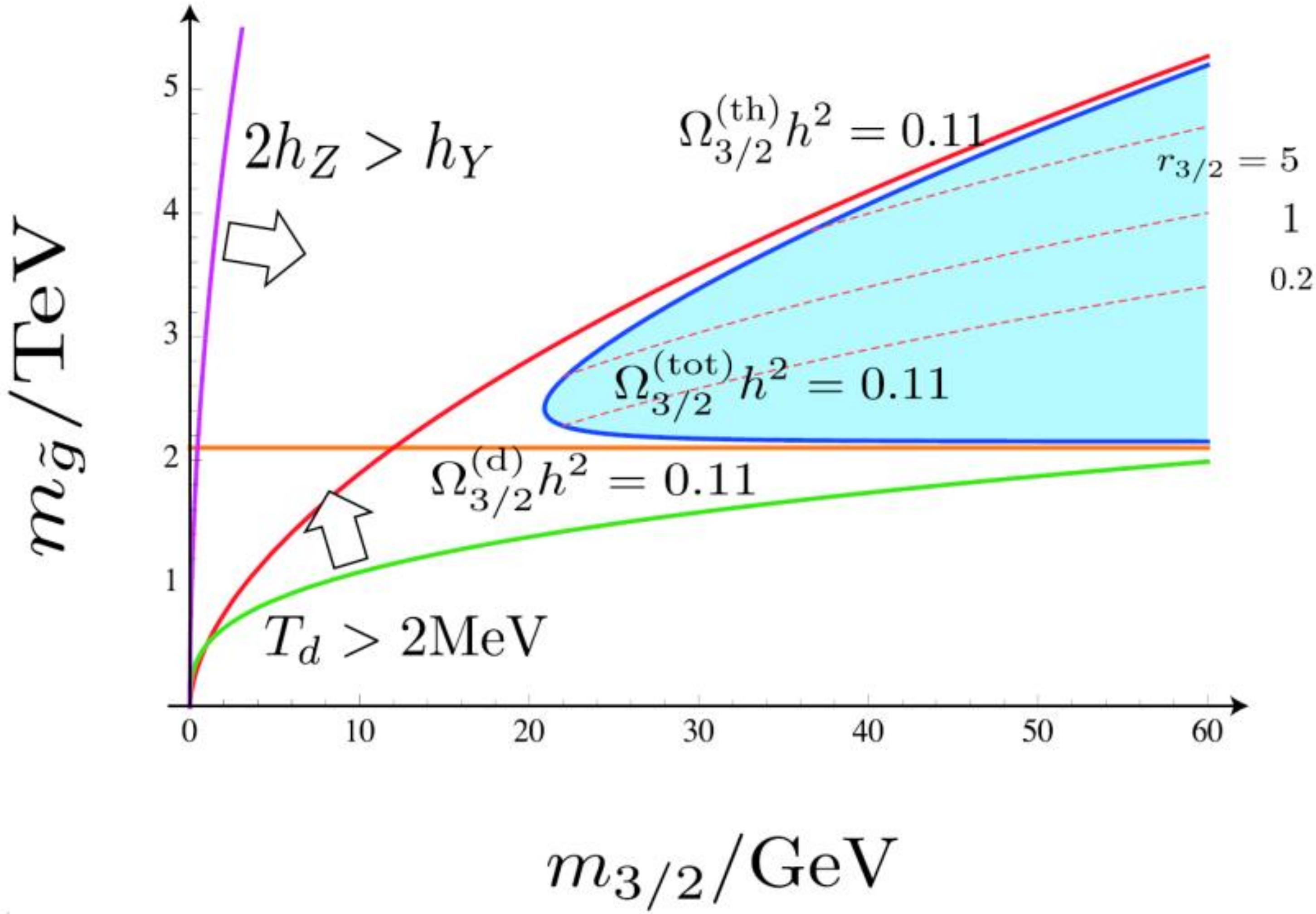
- SUSY breaking global minimum :

$$\langle |S|^2 \rangle = \frac{|m_S^2|}{2\kappa^2}, \quad \langle q \rangle = \langle \tilde{q} \rangle = \langle E \rangle = \langle \tilde{E} \rangle = 0 \qquad V_0 = -\frac{m_S^4}{4\kappa^2}$$

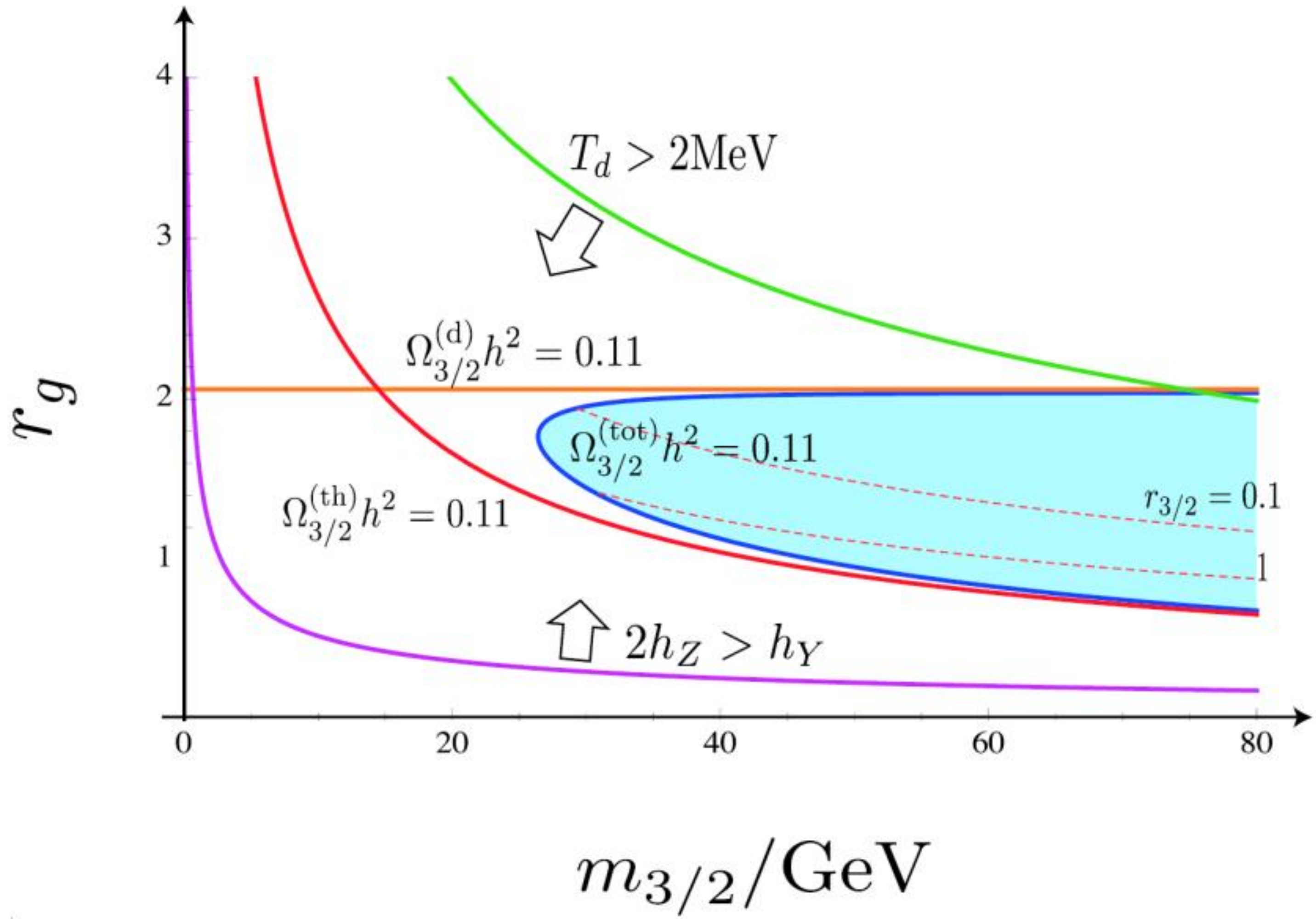
S is determined uniquely and
pseudomoduli space does not exist in the messenger sector.

- Gaugino mass : $m_{\tilde{g}} \sim \frac{\langle |F_S| \rangle}{\langle S \rangle} = \frac{|m_S|}{\sqrt{2}}$

Leading order gaugino mass is nonzero on the global minimum !



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



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