Inflation and gravitino dark matter embedded in gauge-mediated SUSY-breaking mechanism

Kohei Kamada (DESY, Theory Group)

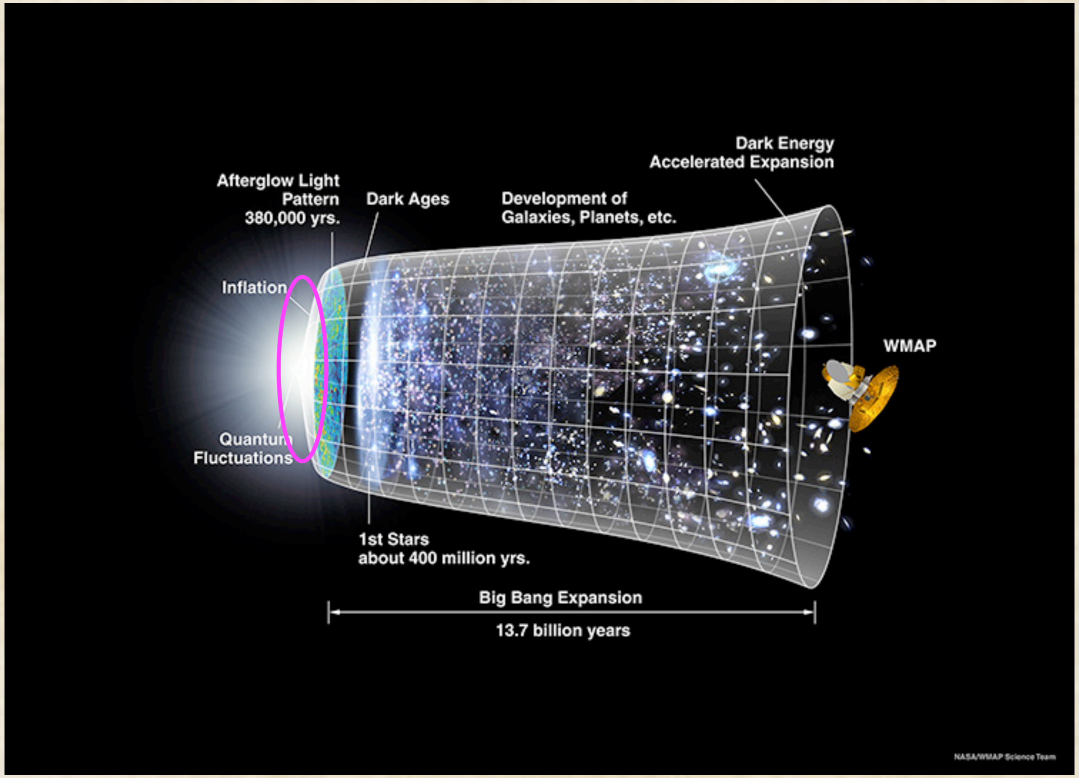
DESY theory workshop
Cosmology meets Particle Physics :
Ideas and Measurements

based on KK, Y.Nakai and M.Sakai (Kyoto U),
Prog. Theo. Phys. 126 (2011) 35, arXiv:1103.5097 [hep-ph]

Introduction

Inflation... solution of many cosmological problems

horizon/flatness problem, origin of primordial perturbation



How to embed inflation in the model of high energy physics?

Inflation models embedded in high energy physics models

- GUT Higgs ('84 Shafi+ and so on...)
- Right-handed scalar neutrino ('93 Murayama+)
- String inspired models ('04 Kachru+ and so on...)
- Flat direction in the MSSM ('06 Allahverdi+)
- Standard model Higgs ('08 Bezrukov+, '11 KK+)
- and so on...

This talk

… Inflation from SUSY-breaking sector

We propose

an inflationary scenario that does not need any additional degrees of freedom in a gauge-mediated SUSY-braking model

This model can predict

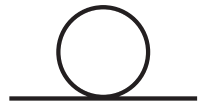
healthy cosmic history … NO gravitino/moduli problem

testable model parameters such as gaugino mass

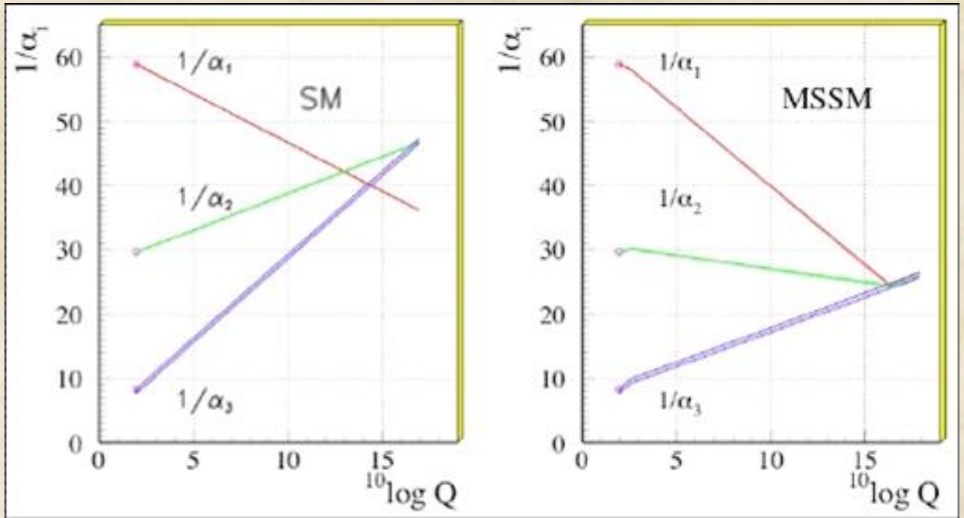
Why SUSY ?

✓ SUSY(supersymmetry) is one of the most promising models beyond the standard model of particle physics

- Hierarchy problem, gauge coupling unification

$$m^2_{\mathrm{Higgs}} = m^2_{\mathrm{Higgs},0} +$$  $$+$$ 

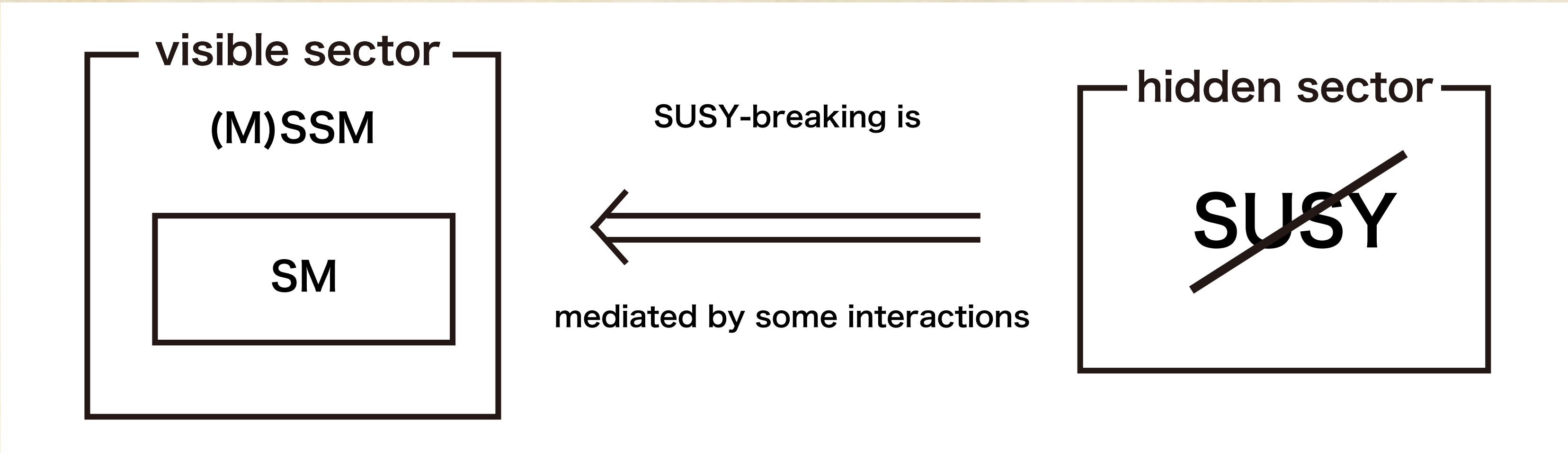
$$\simeq m^2_{\mathrm{Higgs},0} + m^2_{\mathrm{soft}}$$



Why SUSY-breaking ?

✓SUSY predicts "SUSY particles" whose masses and other properties are the same as the SM particle other than their spin.

✓SUSY must be broken at a high-energy scale outside the MSSM sector.



Otherwise SUSY particles must have been detected already.

Here we consider ...
a gauge-mediated SUSY-breaking model

SUSY-breaking in the hidden sector is transmitted to the visible sector by the standard model gauge interactions.

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

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

$$(m \gg \mu, m_Z)$$

	$SU(N)$	$U(1)_1$	$U(1)_2$	$U(1)_R$
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

Vacuum structure

SUSY breaking vacuum:

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

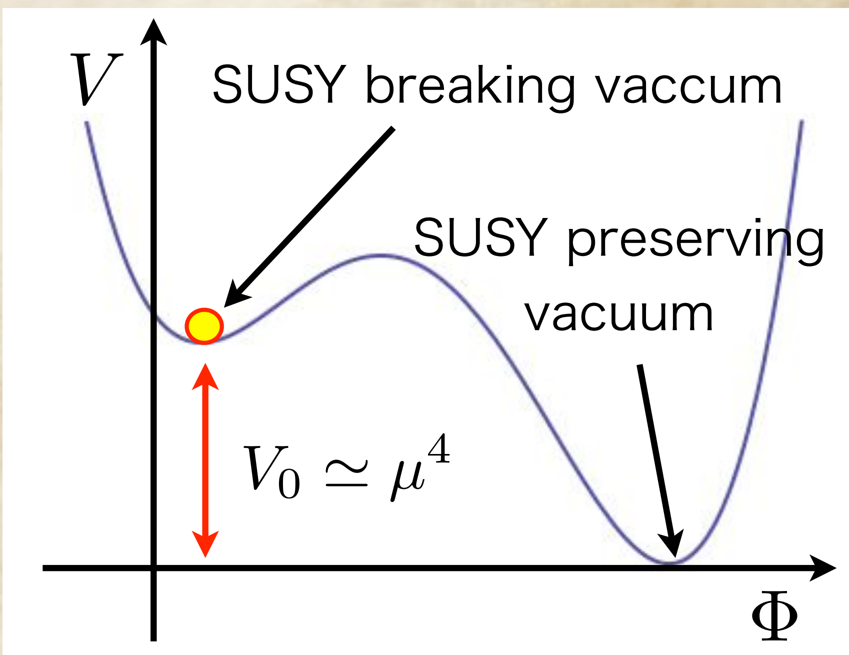
Φ : pseudomoduli

... stabilized one-loop effect

uplifted SUSY breaking vacuum

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

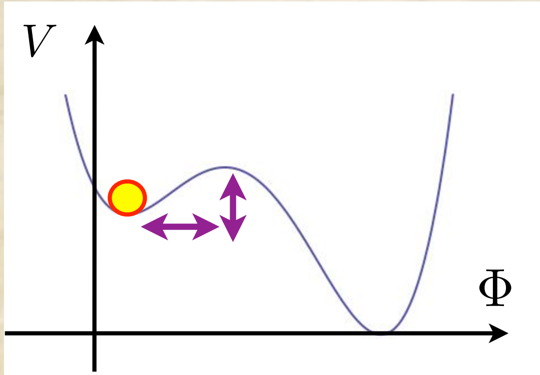
$$m_\Phi^2 \simeq \frac{N}{64\pi^2}\frac{h_{\rm Y} h_\Phi^4}{h_{\rm Z}^2}\frac{\mu^4}{m^2} \equiv m_{\rm CW}^2.$$



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

Vacuum structure

Vacuum stability is guaranteed by the non-vanishing expectation values of $\chi, \bar{\chi}$



$$\Gamma_{\rm vac} \propto e^{-S}$$

$$S \sim \frac{h_Z^8}{h_{\rm Y}^4 h_\Phi^4} \left(\frac{m}{m_Z}\right)^4 \left(\frac{m}{\mu}\right)^4$$

$$(m \gg \mu, m_Z)$$

Identifying the SU(N) global symmetry is the gauge symmetry of the visible sector that includes the standard model gauge symmetry as a subgroup,

$\rho, \bar{\rho}, Z, \bar{Z}$ act as messengers ... gauge mediation

$$m_{\lambda_i} \simeq \frac{g_i^2}{16\pi^2} \frac{h_{\rm Y} h_\Phi}{h_{\rm Z}^2} \frac{\mu^2}{m} \frac{m_{\rm Z}}{m},$$

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

The emergence of gaugino mass is guaranteed by the existence of lower vacuum.

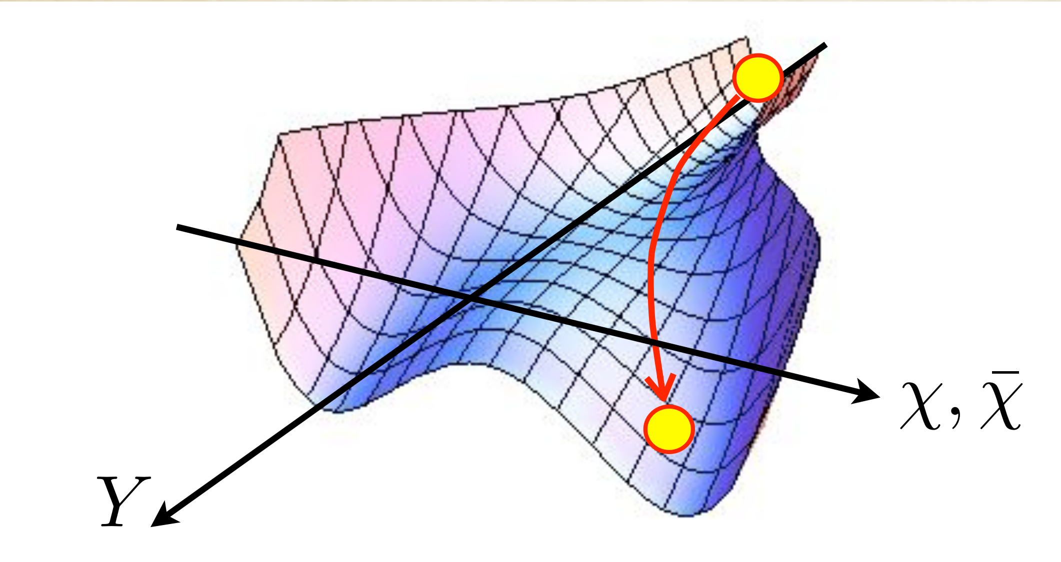
✓ All the fields are essential for SUSY breaking.

✓ A hybrid inflation is embedded in this model without introducing other degree of freedom.

✓ Consistent cosmic history is realized with appropriate parameter choices.

✓ SUSY-breaking vacuum is chosen after hybrid inflation naturally.

Realization of hybrid inflation



$$W = m^2 Y - h_Y \chi Y \bar{\chi}$$

-inflaton: Y

-waterfall-field: $\chi, \bar{\chi}$

$$V \simeq |m^2 - h_Y \chi\bar{\chi}|^2 + h_Y^2 |Y|^2 (|\chi|^2 + |\bar{\chi}|^2) + \underbrace{\frac{h_Y^2 m^4}{16\pi^2} \log\left(\frac{h_Y^2 |Y|^2}{\Lambda^2}\right)}_{\text{quantum correction}}$$

waterfall fields become tachyonic @$|Y| \simeq \dfrac{m}{\sqrt{h_Y}}$ and inflation ends.

primordial perturbation: $\mathcal{P}_{\mathcal{R}}^{1/2} \simeq \dfrac{4\sqrt{6\pi}}{3} \dfrac{m^3}{h_Y^{5/2} M_{\rm pl}^3}$

- small tensor perturbation
- $n_s \simeq 1$
- small non-gaussianity

Hubble induced mass $V \sim 3H^2|\phi|^2$

stabilizes all the fields other than inflaton at the origin.

Problems in inflation models embedded in the SUSY-breaking sector

✓ Are SM sector fields thermalized properly?

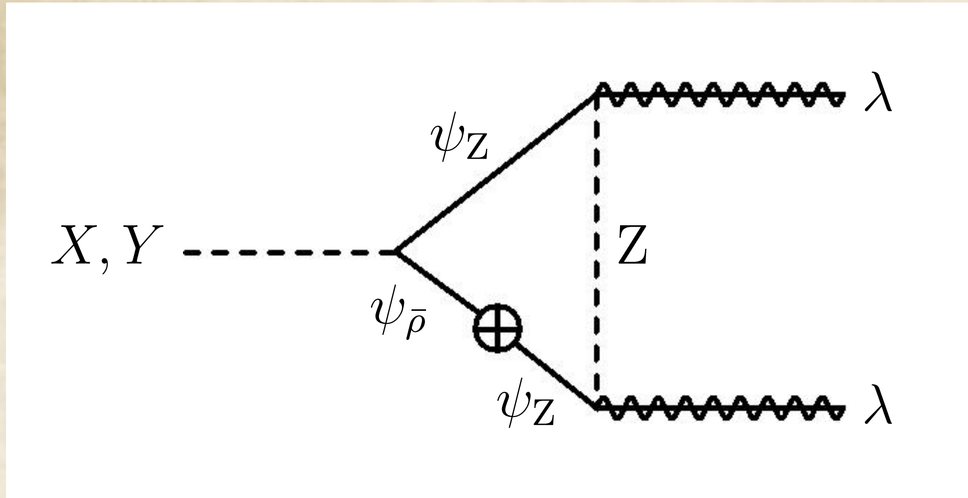
✓ Is the SUSY-breaking vacuum correctly selected?

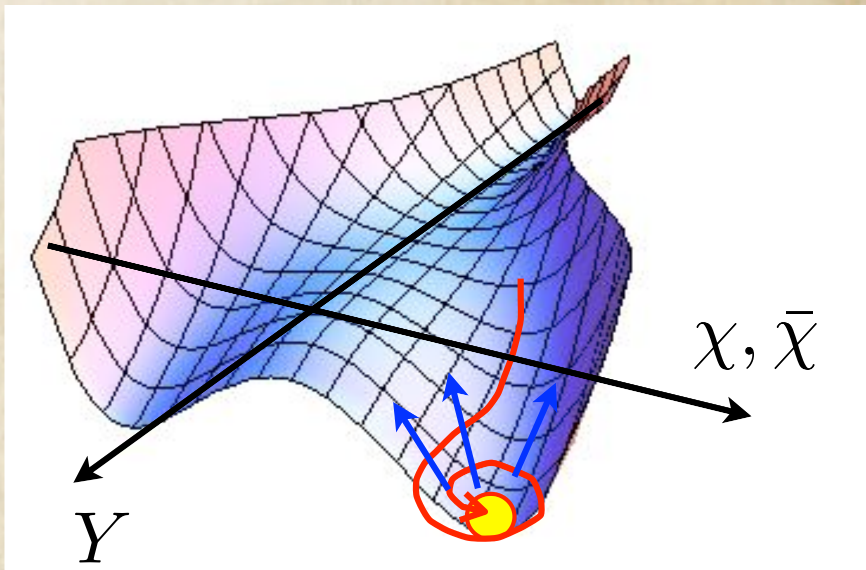
✓ Are not undesirable fields such as gravitinos substantially produced?

Inflaton decay

-Inflaton decays into SM sector through SM gauge interaction.

-SUSY-breaking sector fields except for moduli fields are as heavy as inflaton and are not thermalized if $2h_Z > h_Y$.



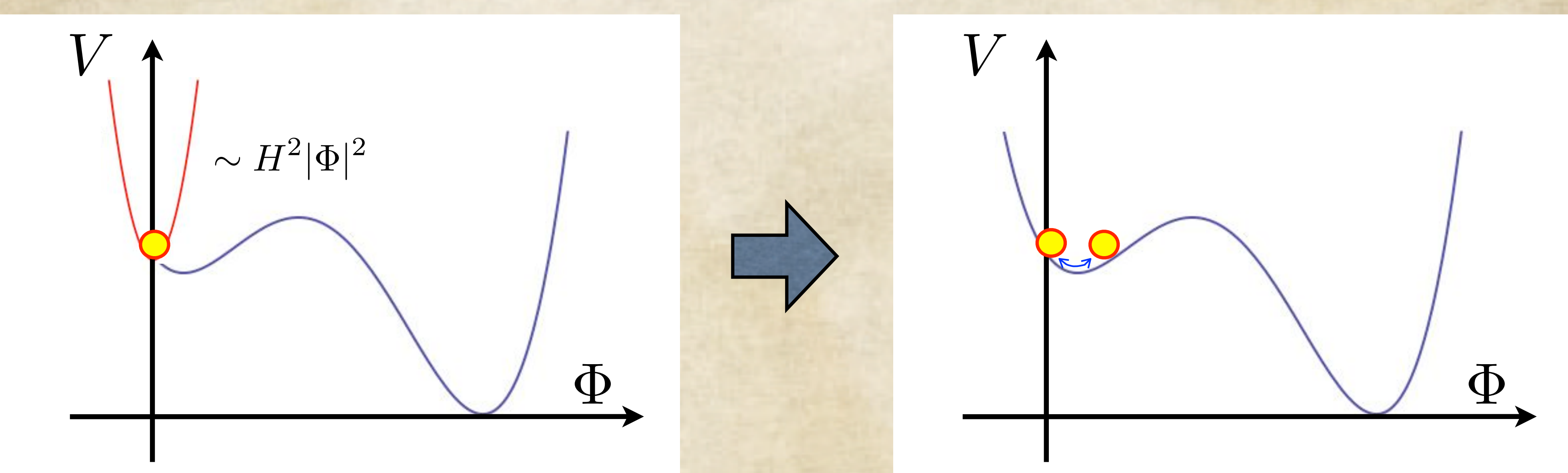


$$T_R \simeq 5.2 \times 10^{10}\mathrm{GeV} \times N^{7/2} \left(\frac{m_{\tilde{g}}}{3.5 m_{\tilde{e}}}\right)^{-6} \left(\frac{m_{3/2}}{15\mathrm{GeV}}\right)^{-3} \left(\frac{m_\Phi}{300\mathrm{GeV}}\right)^{-3} \left(\frac{m_{\tilde{g}}}{1.5\mathrm{TeV}}\right)^{6} \left(\frac{h_Y}{3 \times 10^{-3}}\right)^{17/3}$$

High reheating temperature but gravitino problem does not occur as we will see.

Moduli oscillation

-moduli field stabilizes near the SUSY-breaking vacuum during inflation and starts oscillation later.



During inflation

After inflation

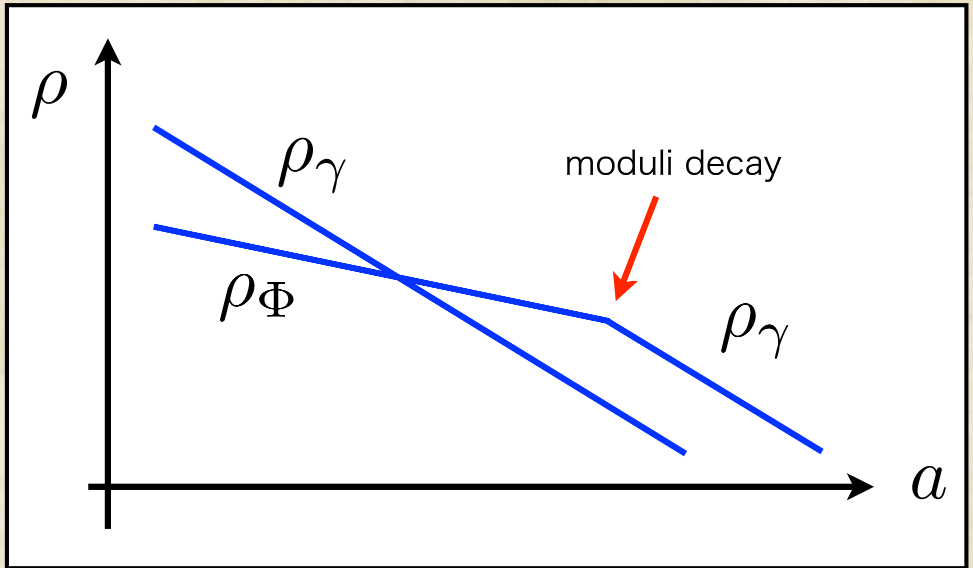
$$\rho_\Phi \propto a^{-3}$$

moduli domination and decay

-moduli field oscillation can dominate the energy density of the Universe but can decay into SM sector before BBN.

-gravitinos may be produced substantially at reheating but can be diluted by moduli decay.

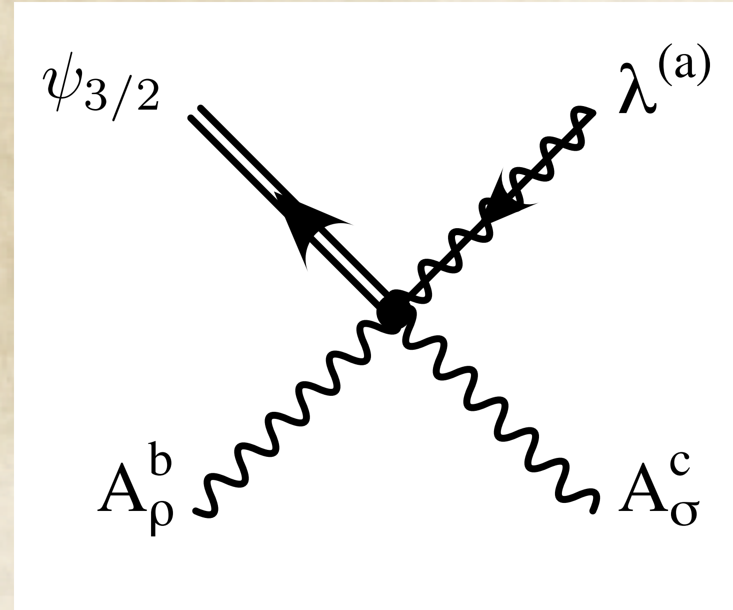
$$T_{\rm d} \simeq 4.4\,{\rm MeV} \times \left(\frac{m_{\tilde{g}}}{3.5 m_{\tilde{e}}}\right)^{-2} \left(\frac{m_{\tilde{g}}}{1.5\,{\rm TeV}}\right)^{3} \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right)^{-1} \left(\frac{m_{\Phi}}{300\,{\rm GeV}}\right)^{-1/2} .$$



Gravitino dark matter

✓ gluino scattering in the thermal plasma

'05 Kawasaki, Kohri and Moroi



$\Rightarrow$ effective at reheating

$$\Omega_{3/2}h^2 \simeq 27 \times \left(\frac{m_{\tilde{g}}}{1.5\text{TeV}}\right)^2 \left(\frac{m_{3/2}}{15\text{GeV}}\right)^{-1} \left(\frac{T_R}{10^{10}\text{GeV}}\right)$$

can be diluted by the moduli decay

$$\Delta^{-1} \simeq \frac{T_d}{T_{\text{dom}}} \simeq 10^{-3}$$

✓ from moduli decay '07 Ibe and Kitano

$$\Phi \longrightarrow \psi_{3/2}\psi_{3/2} \qquad \Omega_{3/2}h^2 \simeq 0.033 \times \left(\frac{m_{\tilde{g}}}{3.5 m_{\tilde{e}}}\right)^2 \left(\frac{m_\Phi}{300\text{GeV}}\right)^{9/2} \left(\frac{m_{\tilde{g}}}{1.5\text{TeV}}\right)^{-3}$$

Constraints on the model

✓ amplitude of primordial perturbation

$$\Rightarrow \mathcal{P}_{\mathcal{R}}^{1/2} \simeq 4.9 \times 10^{-5} \quad \text{(WMAP)}$$

✓ moduli must decay before BBN

$$\Rightarrow T_d \gtrsim 2\mathrm{MeV}$$

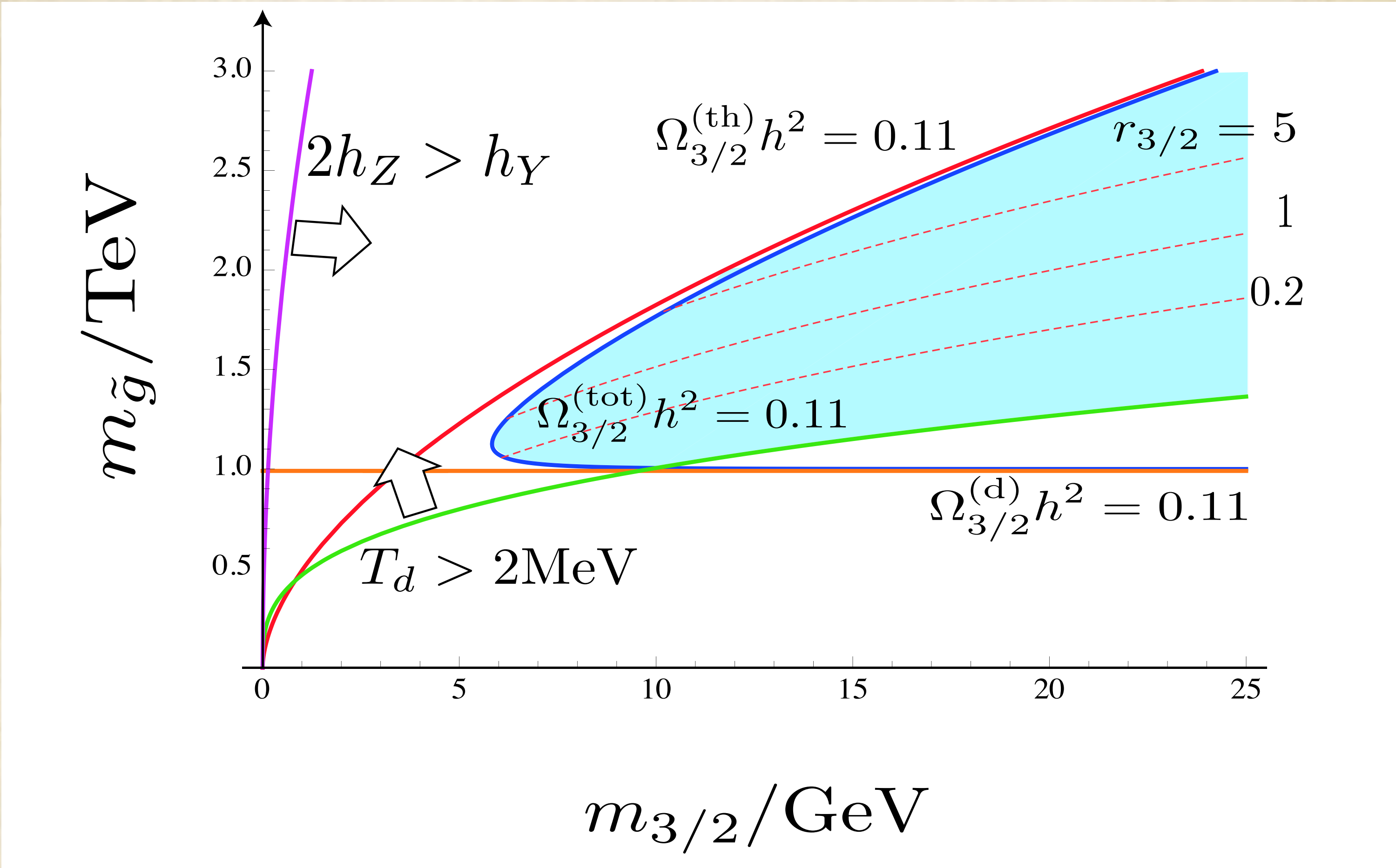
✓ Gravitinos must not overclose the Universe

$$\Rightarrow \Omega_{3/2} h^2 \lesssim 0.11$$

These conditions determine
the allowed parameter region

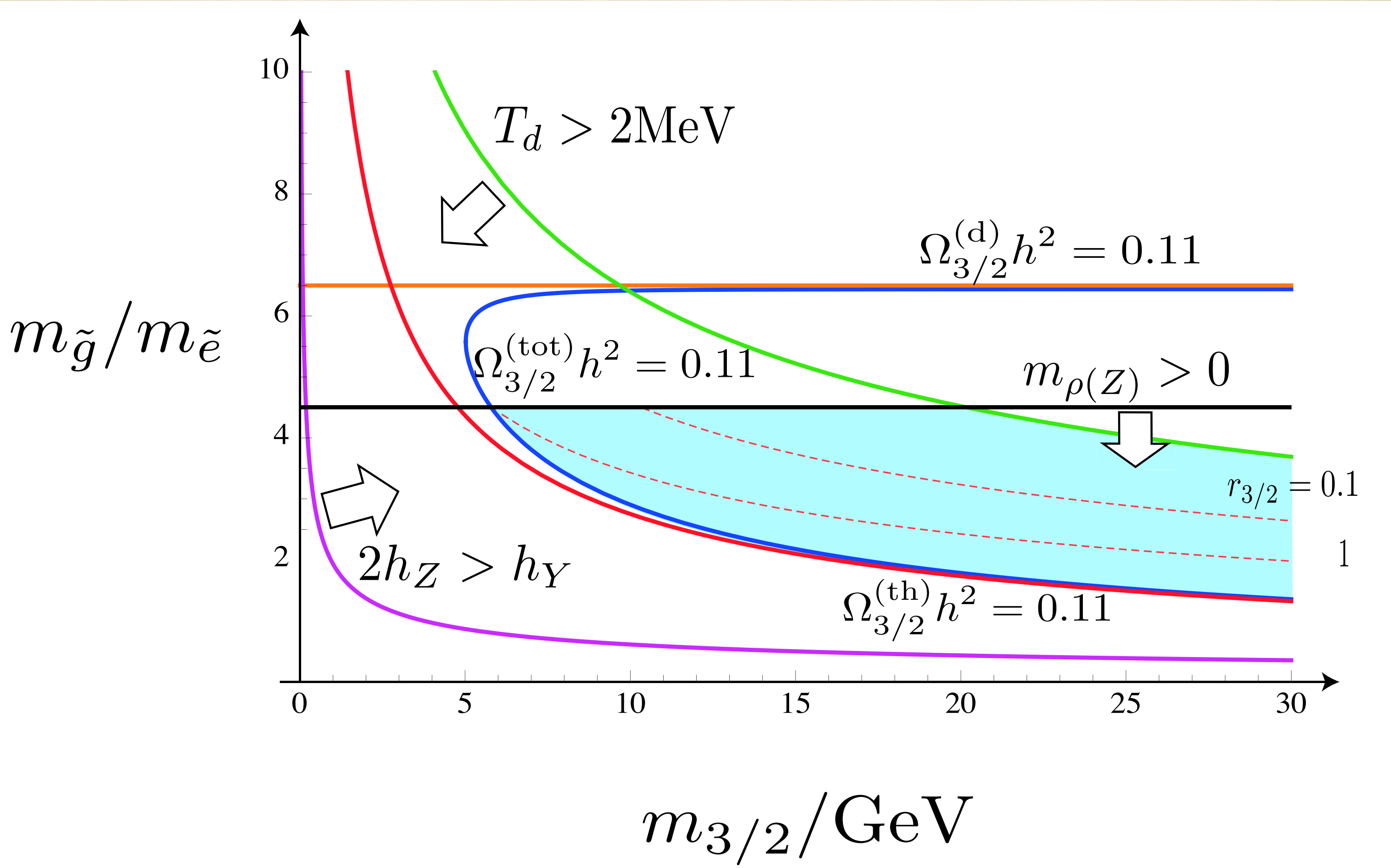
Allowed parameter region

$$m_\Phi = 300\text{GeV}, \quad \frac{m_{\tilde{g}}}{m_{\tilde{e}}} = 3.5, \quad h_Y \simeq 2 \times 10^{-3}$$



Allowed parameter region

$$m_\Phi = 300\mathrm{GeV}, \quad m_{\tilde{g}} \simeq 1.5\mathrm{TeV}, \quad h_Y \simeq 2\times 10^{-3}$$



Conclusion & Discussion

✓ Inflation model embedded in SUSY-breaking model

✓ Successful inflationary scenario and reheating

✓ Gravitino dark matter

✓ Problems

-cosmic string

→ modification of vacuum structure, shifted hybrid inflation

-baryogenesis → Affleck-Dine mechanism?

new baryogenesis mechanism associated with SUSY-breaking sector

Appendix

-gauge mediation

⇒ No Flavor Changing Neutral Current Problem

$$\mu \cancel{\to e}\gamma$$

-meta-stable vacuum

⇒ - Relatively easy model building

- Sizable gaugino mass is generated

(thanks to the R-breaking term of $Z, \bar{Z}$)

One of the most successful SUSY-breaking models !

Vacuum structure

mass spectrum of the SUSY-breaking sector

	Fermions			Bosons		
	Weyl mult.	mass	$SU(N)$	Real mult.	mass	$SU(N)$
Φ	1	0	$\mathbf{1}$	2	m_{CW}	$\mathbf{1}$
$Y,\ \chi,\ \bar{\chi}$	1	$\mathcal{O}(\sqrt{h_{\mathrm{Y}}}m)$	$\mathbf{1}$	2	$\mathcal{O}(\sqrt{h_{\mathrm{Y}}}m)$	$\mathbf{1}$
	1	$\mathcal{O}(\sqrt{h_{\mathrm{Y}}}m)$	$\mathbf{1}$	2	$\mathcal{O}(\sqrt{h_{\mathrm{Y}}}m)$	$\mathbf{1}$
	1	$g_{\mathrm{V}}\frac{m}{\sqrt{h_{\mathrm{Y}}}}$	$\mathbf{1}$	2	$g_{\mathrm{V}}\frac{m}{\sqrt{h_{\mathrm{Y}}}}$	$\mathbf{1}$
$Z,\ \bar{Z},\ \rho,\ \bar{\rho}$	$2N$	$\mathcal{O}(\frac{h_{\mathrm{Z}}}{\sqrt{h_{\mathrm{Y}}}}m)$	$\Box + \bar{\Box}$	$4N$	$\mathcal{O}(\frac{h_{\mathrm{Z}}}{\sqrt{h_{\mathrm{Y}}}}m)$	$\Box + \bar{\Box}$
	$2N$	$\mathcal{O}(\frac{h_{\mathrm{Z}}}{\sqrt{h_{\mathrm{Y}}}}m)$	$\Box + \bar{\Box}$	$4N$	$\mathcal{O}(\frac{h_{\mathrm{Z}}}{\sqrt{h_{\mathrm{Y}}}}m)$	$\Box + \bar{\Box}$

moduli parameters

Effective Kahler

$$K_{\mathrm{eff}} \simeq |\Phi|^2 - \frac{N}{32\pi^2}\mathrm{Tr}\left[MM^\dagger\left(\log\frac{MM^\dagger}{\Lambda^2} - 1\right)\right],$$

$$K_{\mathrm{eff}} \simeq |\Phi|^2 - \frac{N}{32\pi^2}\Bigg[h_\Phi m_{\mathrm{Z}}\left(\Phi + \Phi^\dagger\right) + h_\Phi^2|\Phi|^2 - \frac{1}{8}\frac{h_{\mathrm{Y}}h_\Phi^3}{h_{\mathrm{Z}}^2}\frac{m_{\mathrm{Z}}}{m^2}|\Phi|^2\left(\Phi + \Phi^\dagger\right) + \frac{1}{8}\frac{h_{\mathrm{Y}}h_\Phi^4}{h_{\mathrm{Z}}^2}\frac{1}{m^2}|\Phi|^4 + \mathcal{O}(m_{\mathrm{Z}}^2)\Bigg].$$

@meta stable vacuum

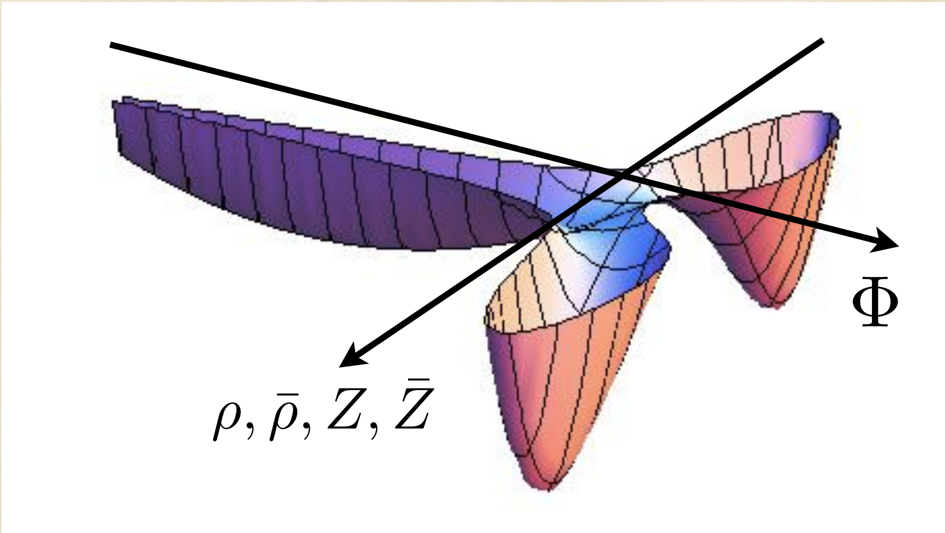
$$|\Phi_0| \simeq \frac{1}{2}\frac{m_{\mathrm{Z}}}{h_\Phi}, \quad \arg\Phi_0 = 0,$$

$$m_\Phi^2 \simeq \frac{N}{64\pi^2}\frac{h_{\mathrm{Y}}h_\Phi^4}{h_{\mathrm{Z}}^2}\frac{\mu^4}{m^2} \equiv m_{\mathrm{CW}}^2.$$

Vacuum structure

SUSY preserving vacuum

$$\chi\bar{\chi} = \frac{m^2}{h_{\mathrm{Y}}}, \quad \rho\bar{\rho} = \frac{\mu^2}{h_{\Phi}}, \quad Z\bar{Z} = \frac{h_{\mathrm{Z}}^2}{h_{\mathrm{Y}} h_{\Phi}} \frac{m^2\mu^2}{m_{\mathrm{Z}}^2},$$
$$Y = \frac{h_{\mathrm{Z}}^2}{h_{\mathrm{Y}} h_{\Phi}} \frac{\mu^2}{m_{\mathrm{Z}}}, \quad \Phi = \frac{h_{\mathrm{Z}}^2}{h_{\mathrm{Y}} h_{\Phi}} \frac{m^2}{m_{\mathrm{Z}}}.$$



soft mass parameters

gravitino mass $$m_{3/2} = \frac{\mu^2}{\sqrt{3} M_{\rm Pl}},$$

gaugino/scalar mass

$$m_{\lambda_i} \simeq \frac{g_i^2}{16\pi^2} F_\Phi \frac{\partial}{\partial \Phi} \log\det M,$$

$$m_{\tilde{f}}^2 \simeq \sum_i C_2^i \left(\frac{g_i^2}{16\pi^2}\right)^2 |F_\Phi|^2 \frac{\partial^2}{\partial\Phi\partial\Phi^\dagger} \sum_s \left(\log|M_s|^2\right)^2,$$

$$\Downarrow$$

$$m_{\lambda_i} \simeq \frac{g_i^2}{16\pi^2} \frac{h_{\rm Y} h_\Phi}{h_{\rm Z}^2} \frac{\mu^2}{m} \frac{m_{\rm Z}}{m},$$

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

Inflationary predictions

power spectrum of the curvature perturbation

$$\mathcal{P}_{\mathcal{R}}^{1/2} \simeq \frac{1}{\sqrt{2\epsilon}}\left(\frac{H}{2\pi M_{\rm Pl}}\right) \simeq \begin{cases} \dfrac{4\sqrt{6\pi}}{3}\dfrac{m^3}{h_{\rm Y}^{5/2}M_{\rm Pl}^3} & \text{for} \quad \mathcal{N} < \dfrac{8\pi^2 m^2}{h_{\rm Y}^3 M_{\rm Pl}^2}, \\ \dfrac{2}{h_{\rm Y}}\sqrt{\dfrac{\mathcal{N}}{3}}\left(\dfrac{m}{M_{\rm Pl}}\right)^2 & \text{for} \quad \mathcal{N} > \dfrac{8\pi^2 m^2}{h_{\rm Y}^3 M_{\rm Pl}^2}. \end{cases}$$

scalar spectral index of primordial curvature perturbation

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

tensor to scalar ratio

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

We mainly investigate the case $h_Y < 3\times 10^{-3}$,

Effective interactions of moduli

$$m_{\tilde{f}}^2(\Phi) = \sum_i C_2^i \left(\frac{g_i^2}{16\pi^2}\right)^2 \left[\frac{h_{\mathrm{Y}} h_\Phi^2}{h_{\mathrm{Z}}^2}\,\frac{\mu^4}{m^2} + \frac{3}{4}\,\frac{h_{\mathrm{Y}}^2 h_\Phi^3}{h_{\mathrm{Z}}^4}\,\frac{\mu^4 m_{\mathrm{Z}}}{m^4}\,(\Phi + \Phi^\dagger) + \cdots\right],$$

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

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

Gravitinos from inflaton decay

$$Y_{3/2} \simeq 7\times 10^{-11}\left(\frac{g_*}{200}\right)^{-\frac{1}{2}}\left(\frac{T_R}{10^6\mathrm{GeV}}\right)^{-1}\left(\frac{\langle\phi\rangle}{10^{15}\mathrm{GeV}}\right)^2\left(\frac{m_\phi}{10^{12}\mathrm{GeV}}\right)^2.$$

'07 Endo Takahashi and Yanagida

Our scenario

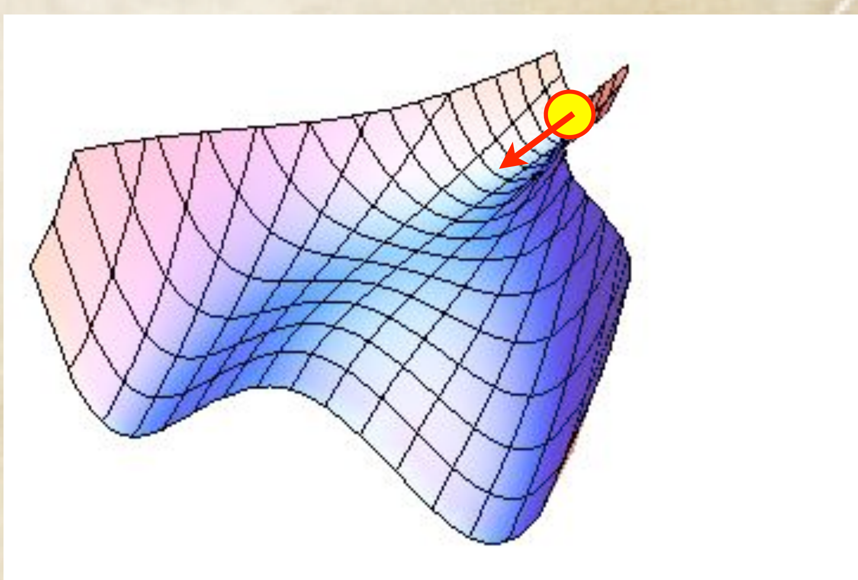
$$T_R \sim 10^{12}\mathrm{GeV} \qquad \langle\chi\rangle \sim 6\times 10^{15}\mathrm{GeV}$$

$$m_\chi \sim 10^{13}\mathrm{GeV} \qquad m_{3/2} \sim 10\mathrm{GeV}$$

gravitino problem from inflaton decay does not occur because of high reheating temperature

Cosmic history

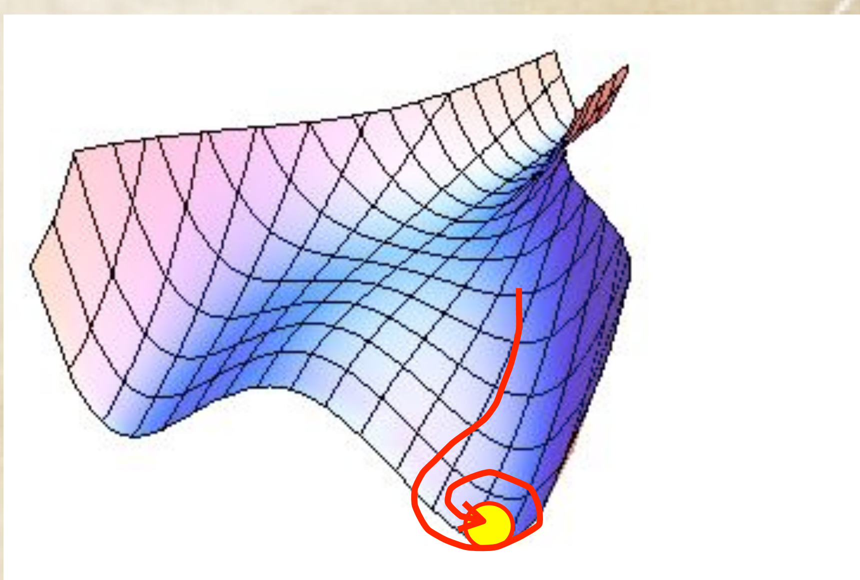
Hybrid inflation
in the SUSY-breaking sector



Cosmic history

Hybrid inflation
in the SUSY-breaking sector

Inflaton and waterfall fields
oscillate around
the potential minimum



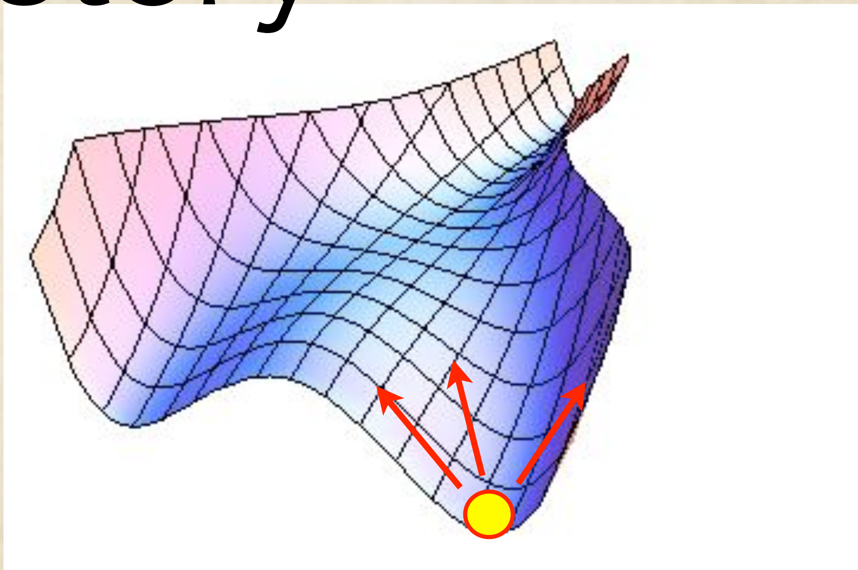
Cosmic history

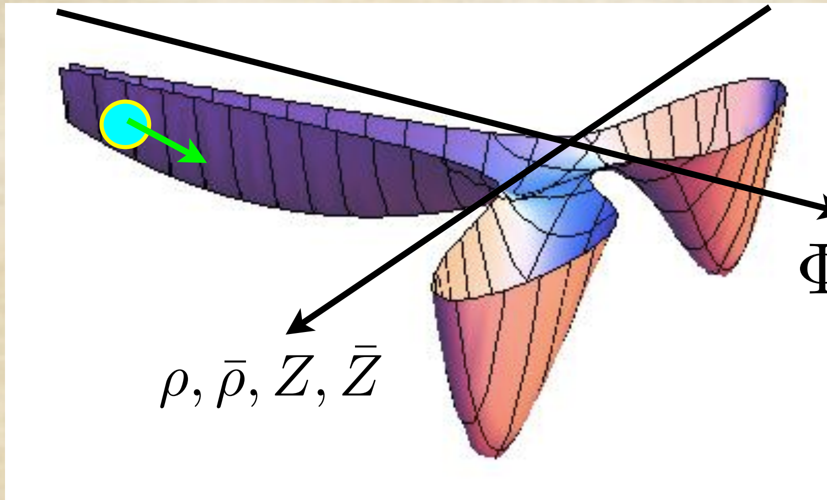
Hybrid inflation
in the SUSY-breaking sector

Inflaton and waterfall fields
oscillate around
the potential minimum

Inflaton and waterfall field decay/
gravitino production/
moduli starts oscillation

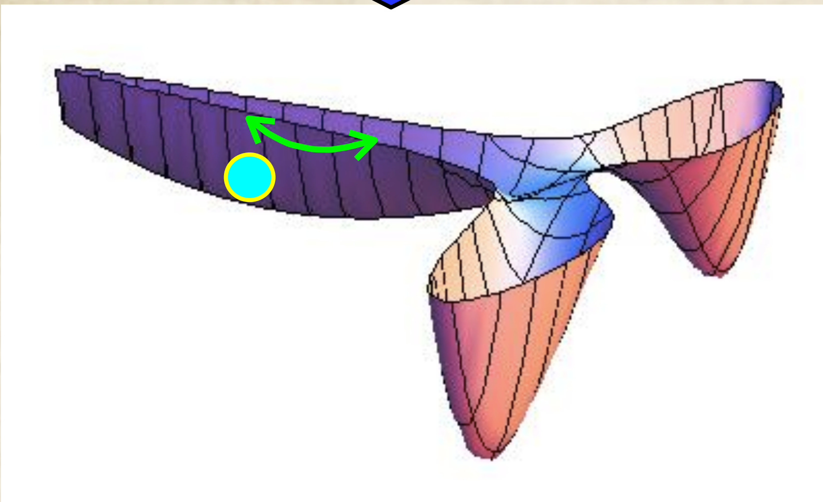
(moduli is stabilized at the origin
during inflation)





Cosmic history

Hybrid inflation
in the SUSY-breaking sector



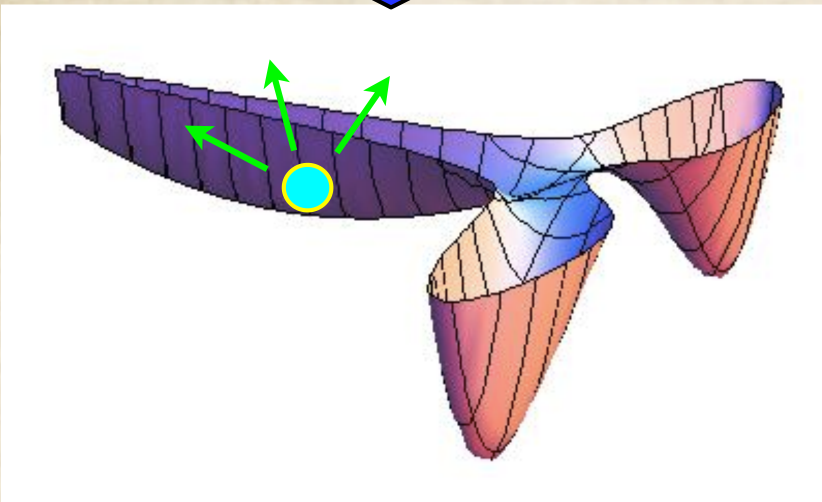
gravitino production/
moduli starts oscillation

(moduli is stabilized at the origin
during inflation)

moduli oscillation (may) dominate
the energy density of the Universe

Cosmic history

Hybrid inflation
in the SUSY-breaking sector



gravitino production/
moduli starts oscillation

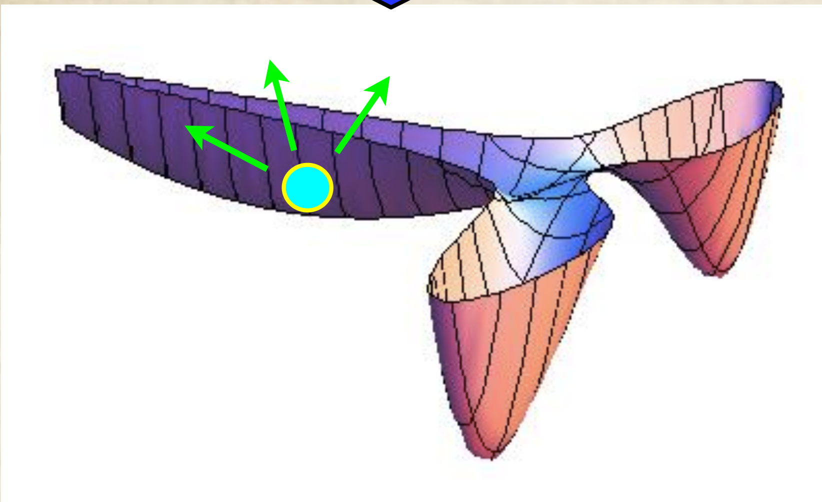
(moduli is stabilized at the origin
during inflation)

moduli oscillation (may) dominate
the energy density of the Universe

moduli decay reheats the Universe

Cosmic history

Hybrid inflation
in the SUSY-breaking sector



gravitino production/
moduli starts oscillation

(moduli is stabilized at the origin
during inflation)

moduli oscillation (may) dominate
the energy density of the Universe

moduli decay reheats the Universe

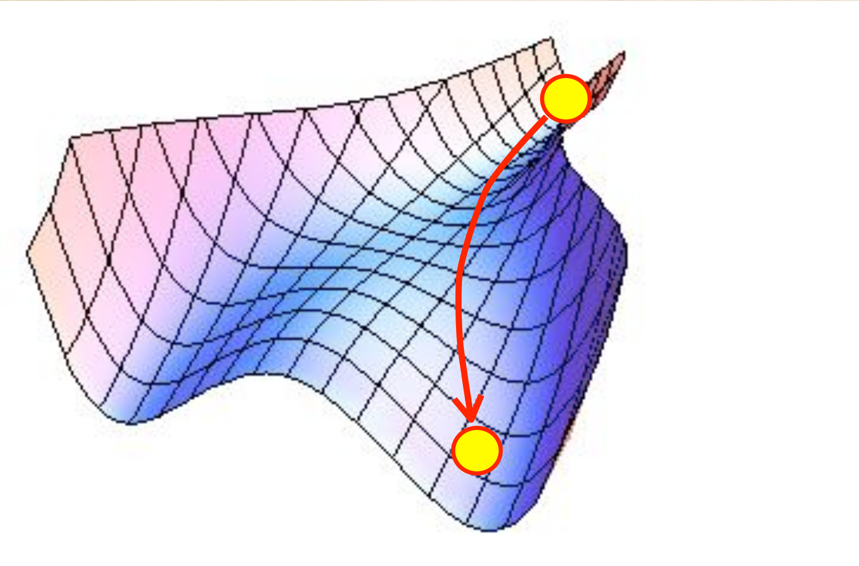
Precise reheating
temperature
Gravitino Dark Matter

testable prediction

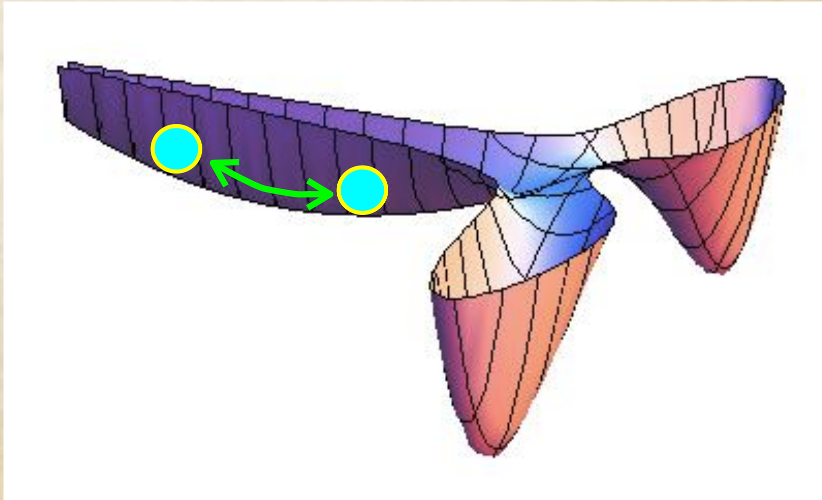
Our model

✓ Hybrid inflation is embedded in the SUSY-breaking model

✓ Moduli oscillation can dilute gravitinos



Hybrid inflation



moduli field oscillates
around the meta-stable vacuum

All the fields are needed for SUSY-breaking !!