Inflation from the supersymmetry breaking sector and the reheating of the universe

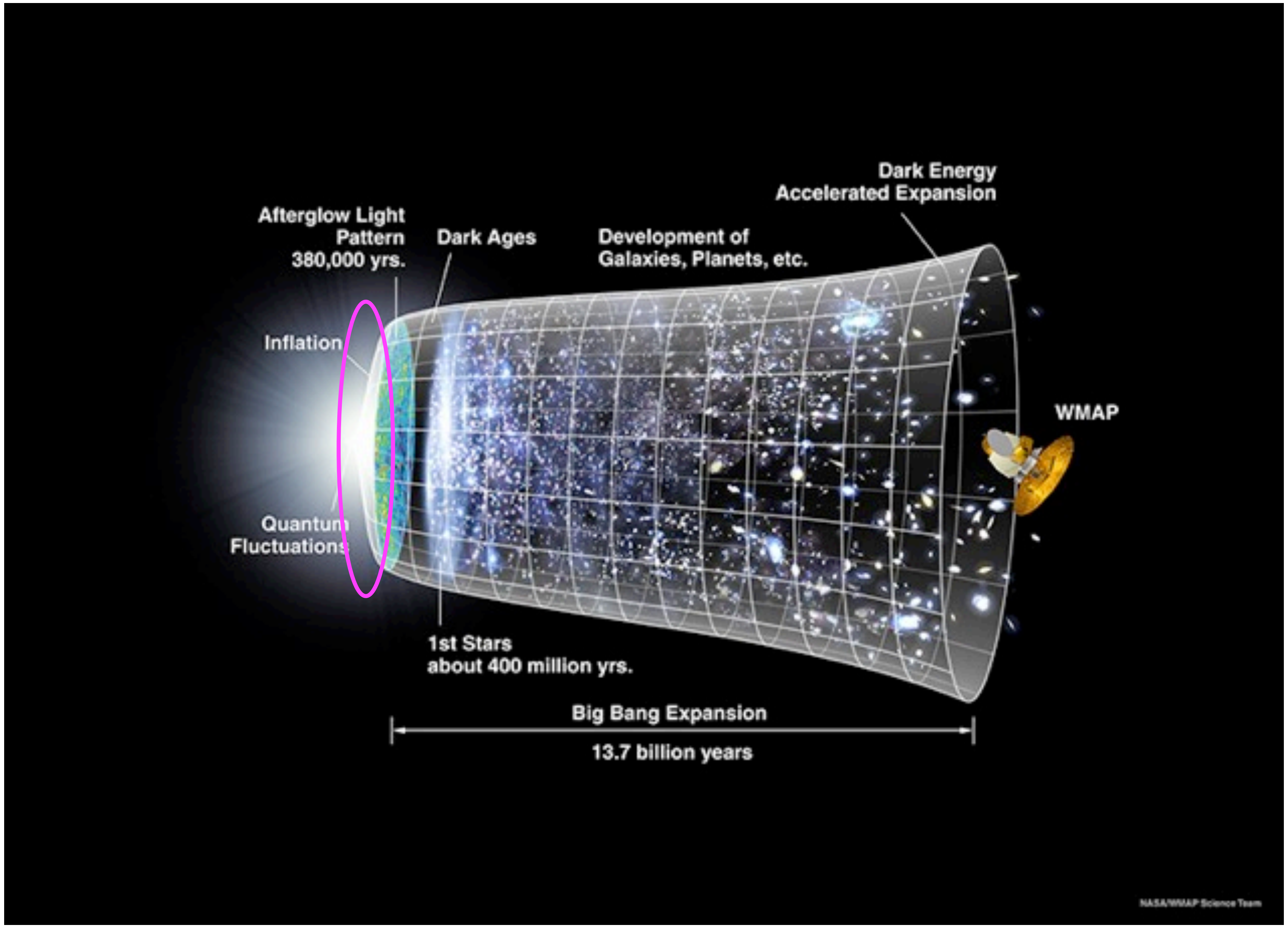
Kohei Kamada (RESCEU, the Univ. of Tokyo)

based on KK, Y.Nakai and M.Sakai, to appear

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

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

This talk

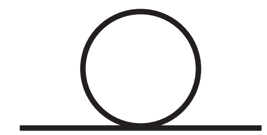
-> Inflation from SUSY-breaking sector

1. Introduction
2. SUSY & its breaking
3. SUSY-breaking and inflation model
4. Problems in the scenario and the solution
5. Conclusion

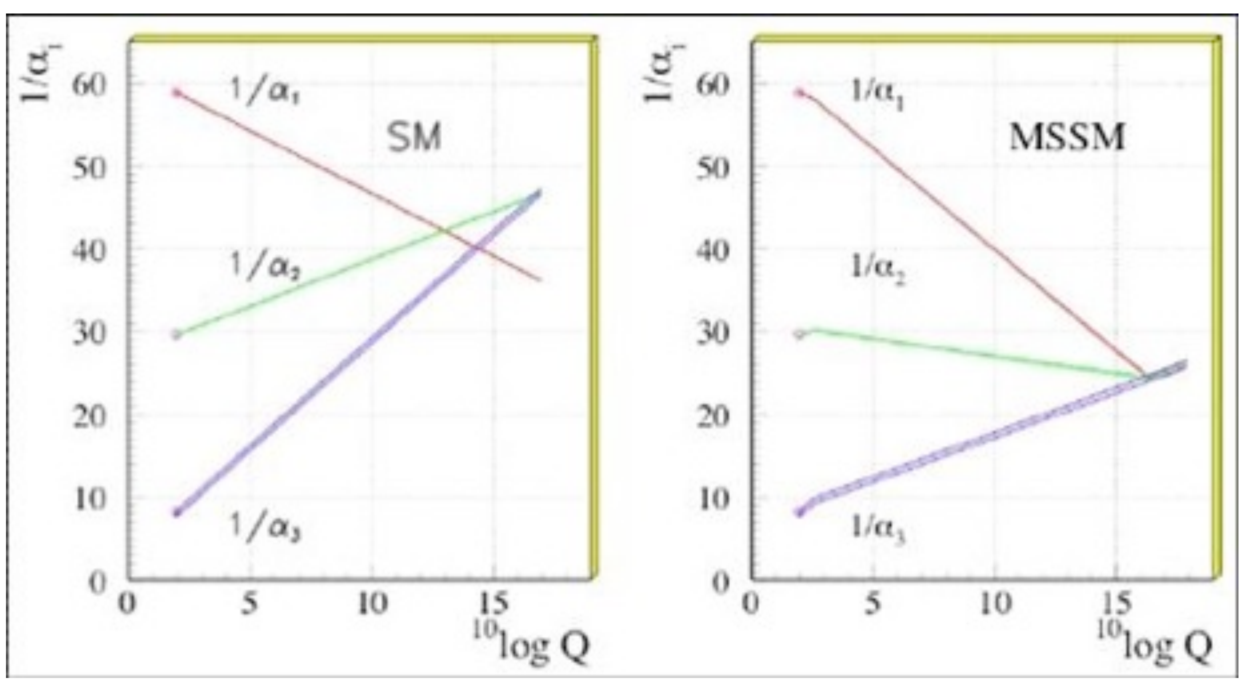
Why SUSY ?

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

- Hierarchy problem, gauge coupling unification

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

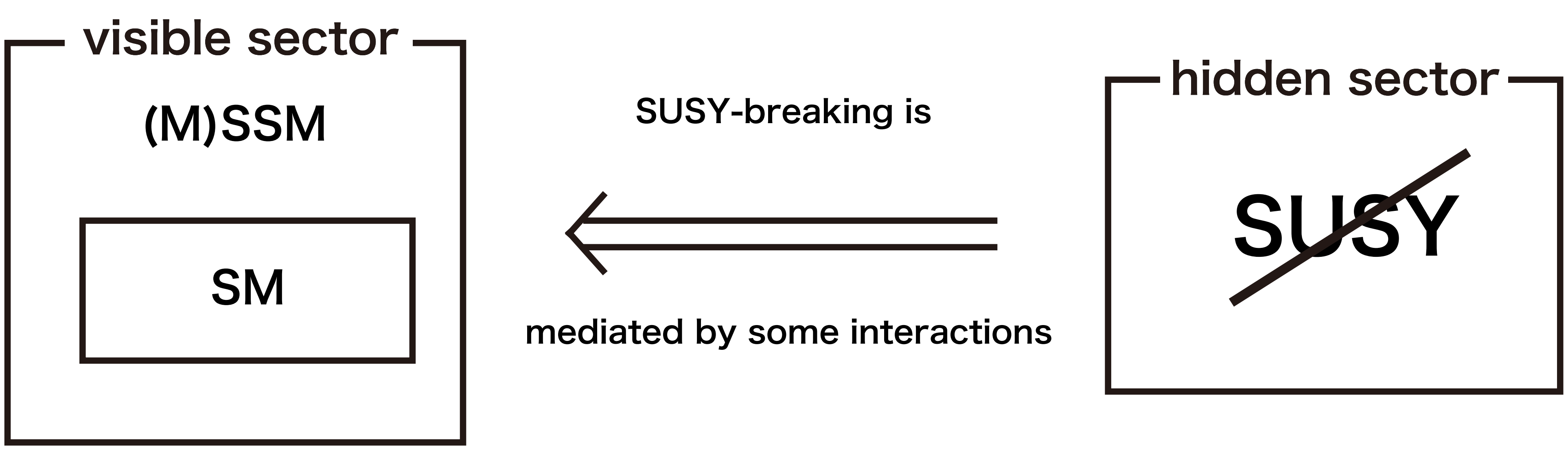
$$\simeq m^2_{\mathrm{Higgs},0} + m^2_{\mathrm{soft}}$$



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 some high-energy scales outside the MSSM sector



Otherwise SUSY particles must have been detected already.

Here we consider SUSY-breaking model mediated by SM gauge interactions

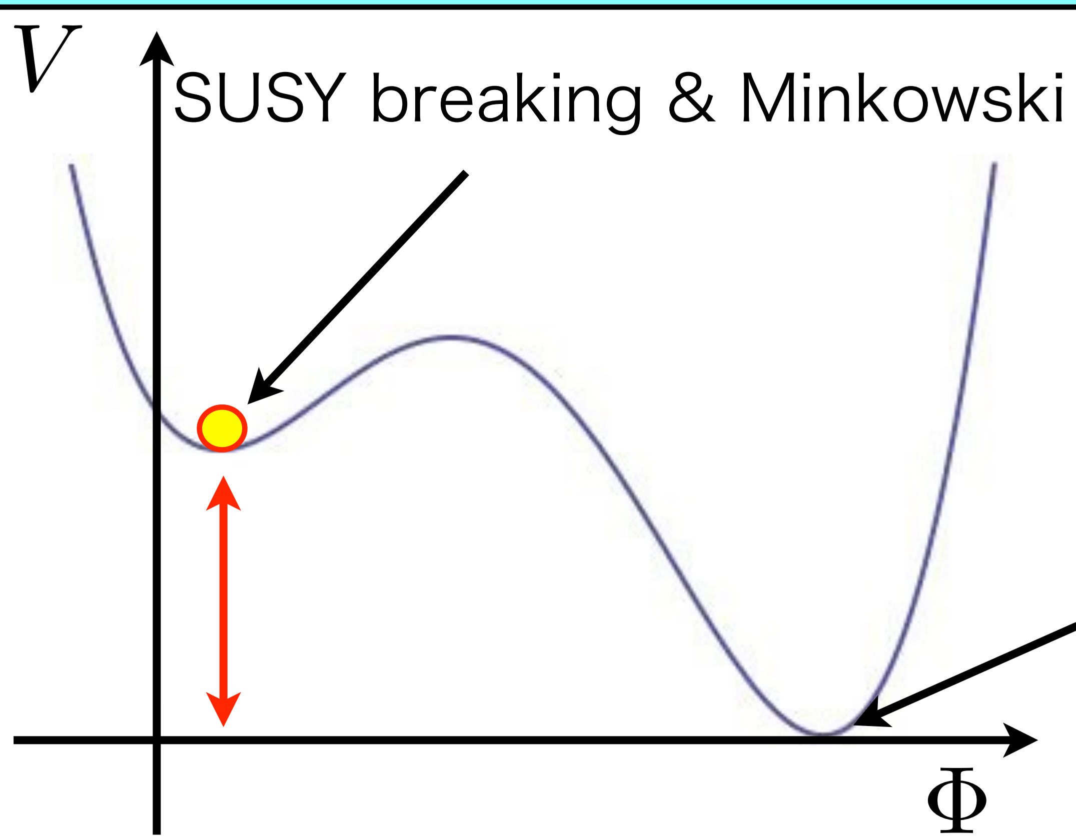
Superpotential for SUSY-breaking sector

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

$$V = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2$$

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

✓Uplifted SUSY-breaking vacuum Φ (moduli)



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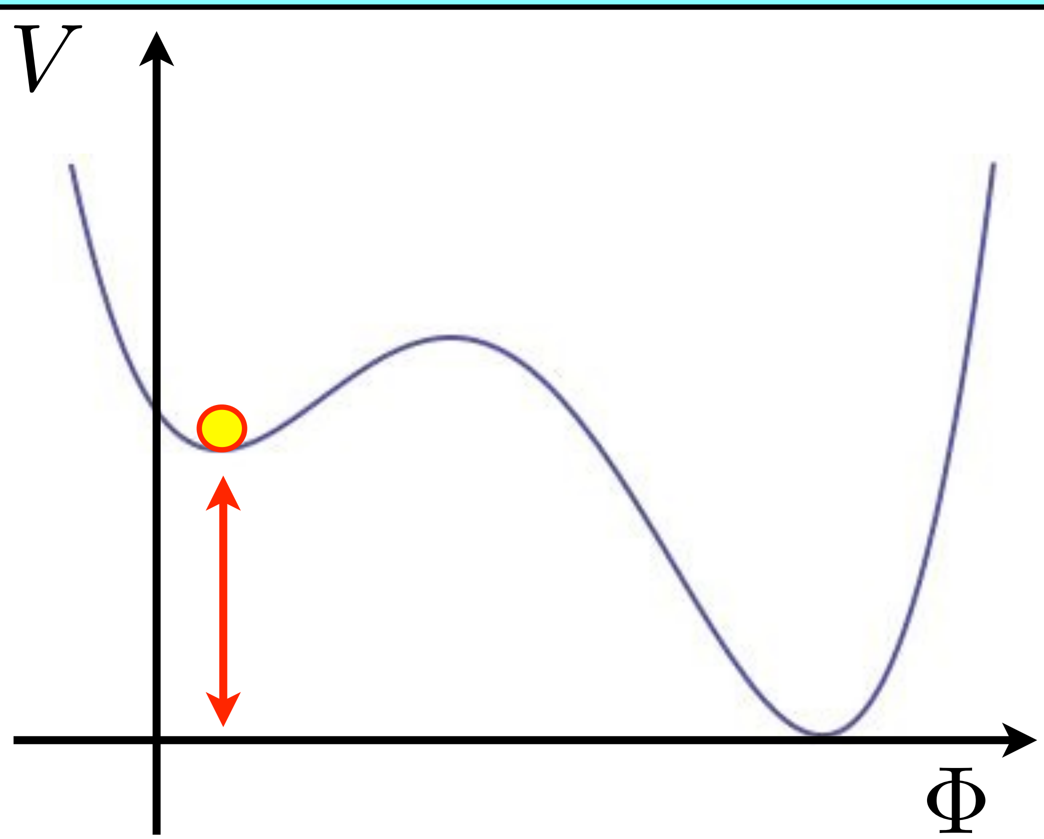
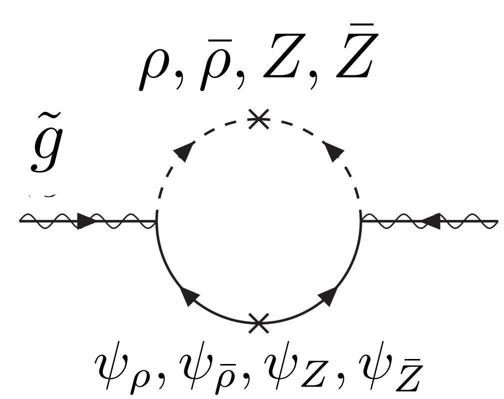
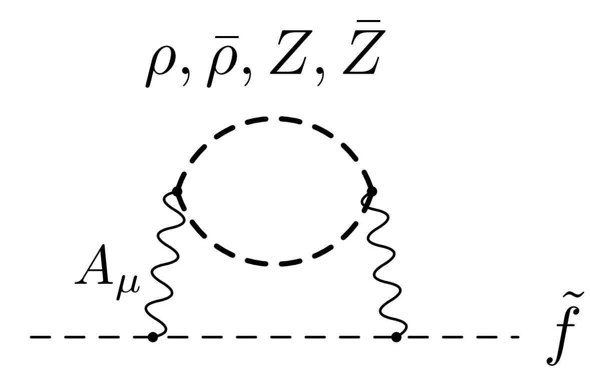


✓ Uplifted SUSY-breaking vacuum Φ (moduli)

✓ $\rho, \bar{\rho}, Z, \bar{Z}$ interact with SM gauge boson and transmit SUSY-breaking effect



gaugino mass



scalar mass

Here we consider SUSY-breaking model mediated by SM gauge interactions

Superpotential for SUSY-breaking sector

$$W = m^2 Y + \mu^2 \Phi - h_Y \chi Y \bar{\chi} - h_\Phi \rho \Phi \bar{\rho}$$
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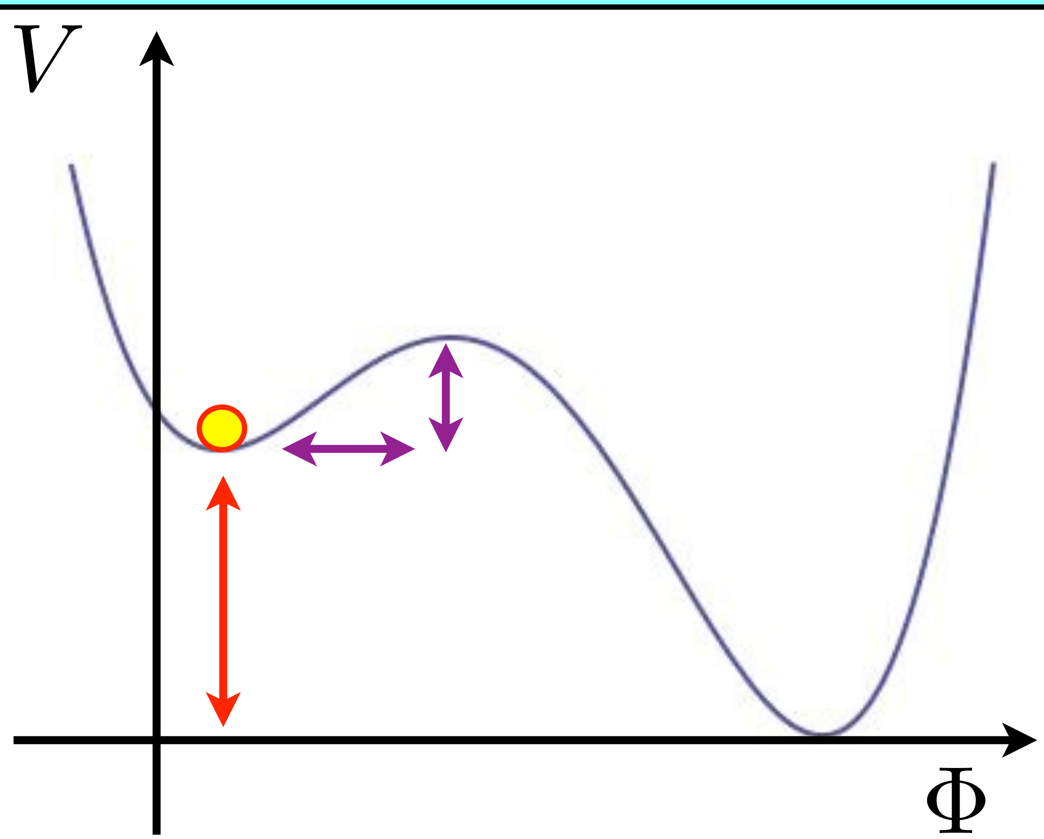


✓ Uplifted SUSY-breaking vacuum Φ (moduli)

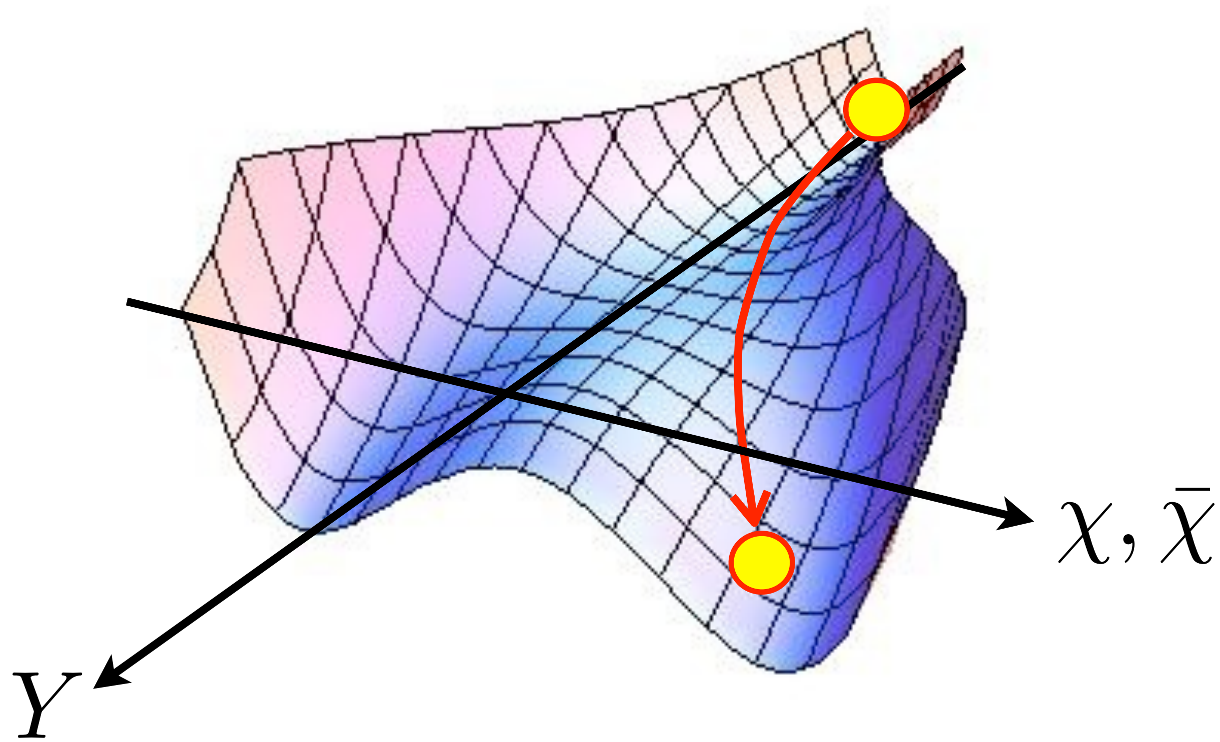
✓ $\rho, \bar{\rho}, Z, \bar{Z}$ interact with SM gauge boson and transmit SUSY-breaking effect

✓ $Y, \chi, \bar{\chi}$ confirm the stability of the SUSY-breaking vacuum

All the fields are needed for SUSY-breaking !

parameters of MSSM fields are determined by model parameters.

We find that hybrid inflation can be embedded in this SUSY-breaking sector



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

-inflaton: Y

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

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

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

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

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

Is that all?

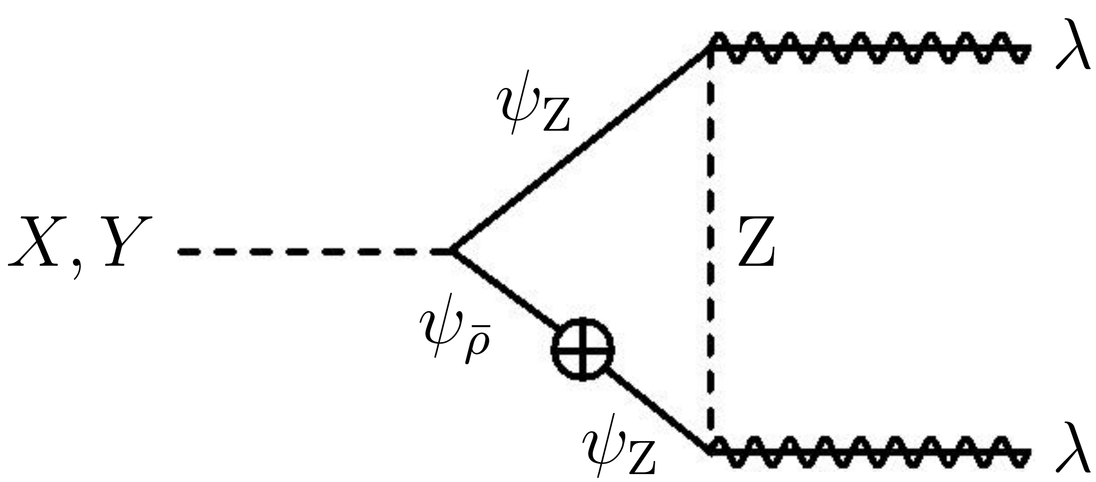
Problems in inflation models embedded in the SUSY-breaking sector

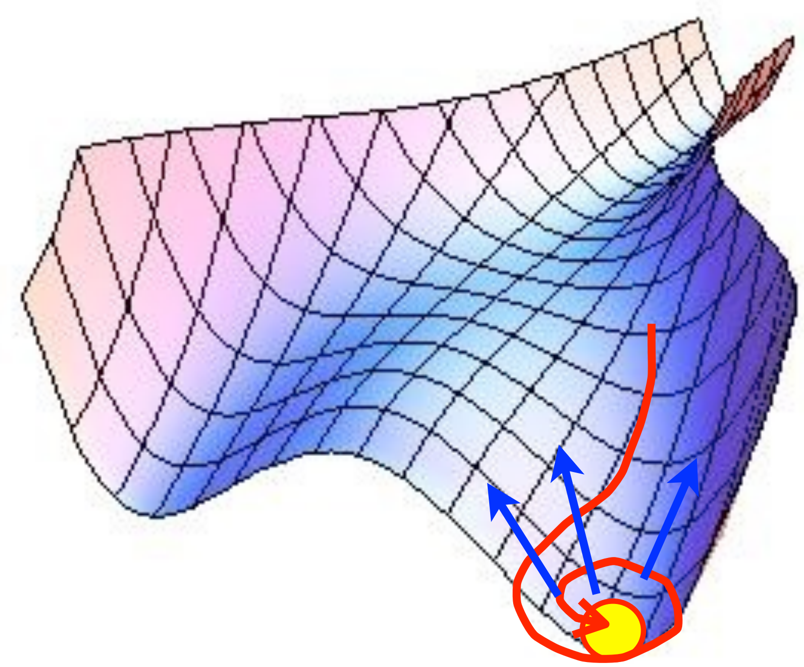
✓ Are SM sector fields thermalized properly?
✓ Is the SUSY-breaking vacuum correctly selected?
✓ Are not undesirable fields such as gravitinos substantially produced?

Our model

-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 $2h_Z > h_Y$.

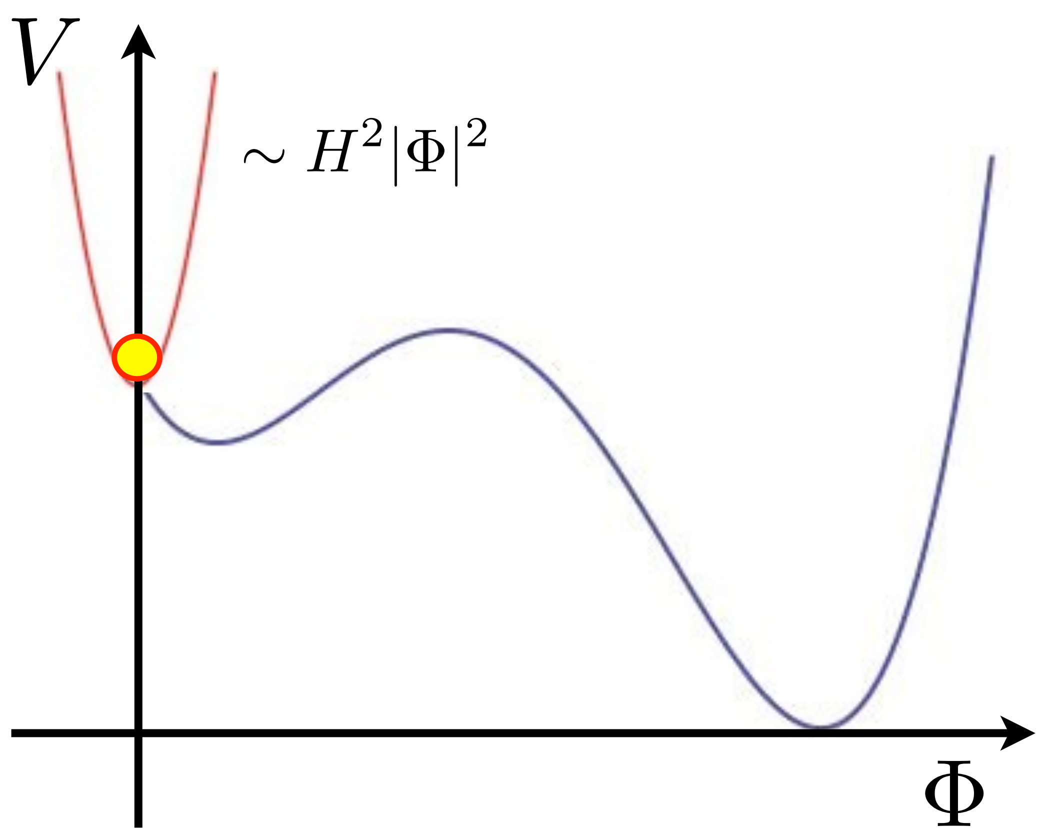




$$T_R \simeq 5.2 \times 10^{10}\mathrm{GeV} \times N^{7/2} \left(\frac{m_{\tilde{g}}}{3.5 m_{\tilde{e}}}\right)^{-6} \left(\frac{m_{3/2}}{15\mathrm{GeV}}\right)^{-3} \left(\frac{m_{\Phi}}{300\mathrm{GeV}}\right)^{-3} \left(\frac{m_{\tilde{g}}}{1.5\mathrm{TeV}}\right)^{6} \left(\frac{h_Y}{3 \times 10^{-3}}\right)^{17/3}$$

Our model

-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 $2h_Z > h_Y$.
-moduli field stabilizes near the SUSY-breaking vacuum during inflation and starts oscillation later.



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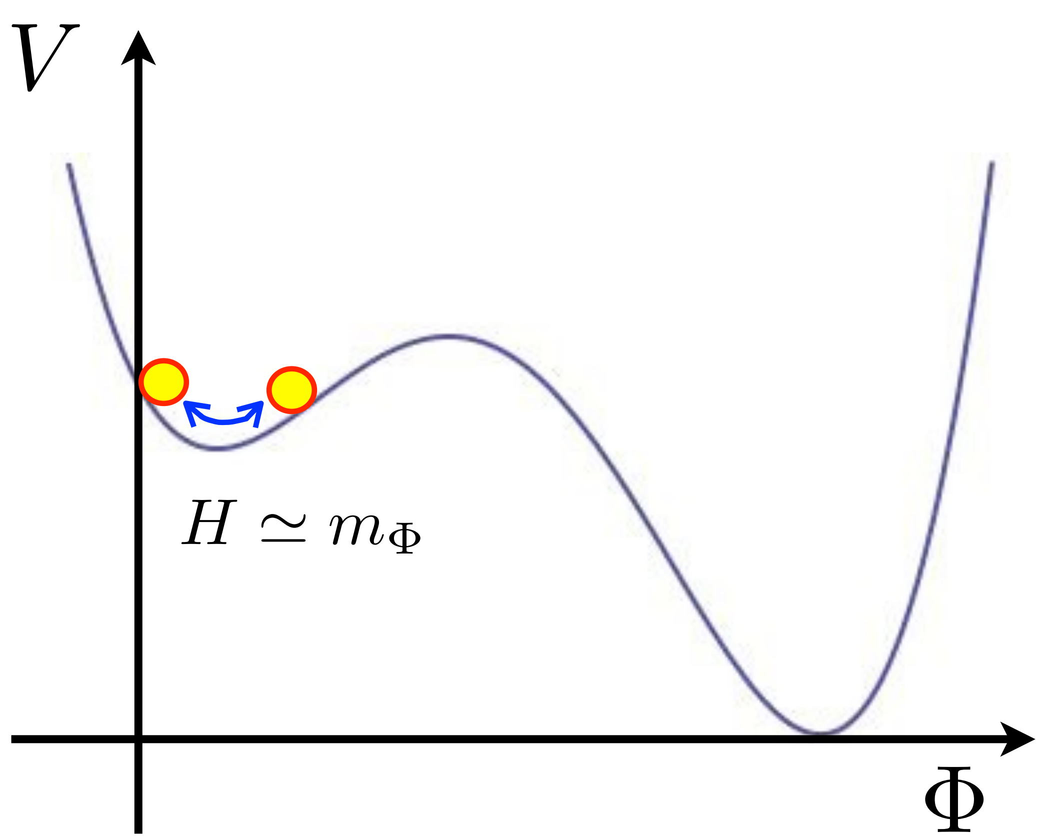
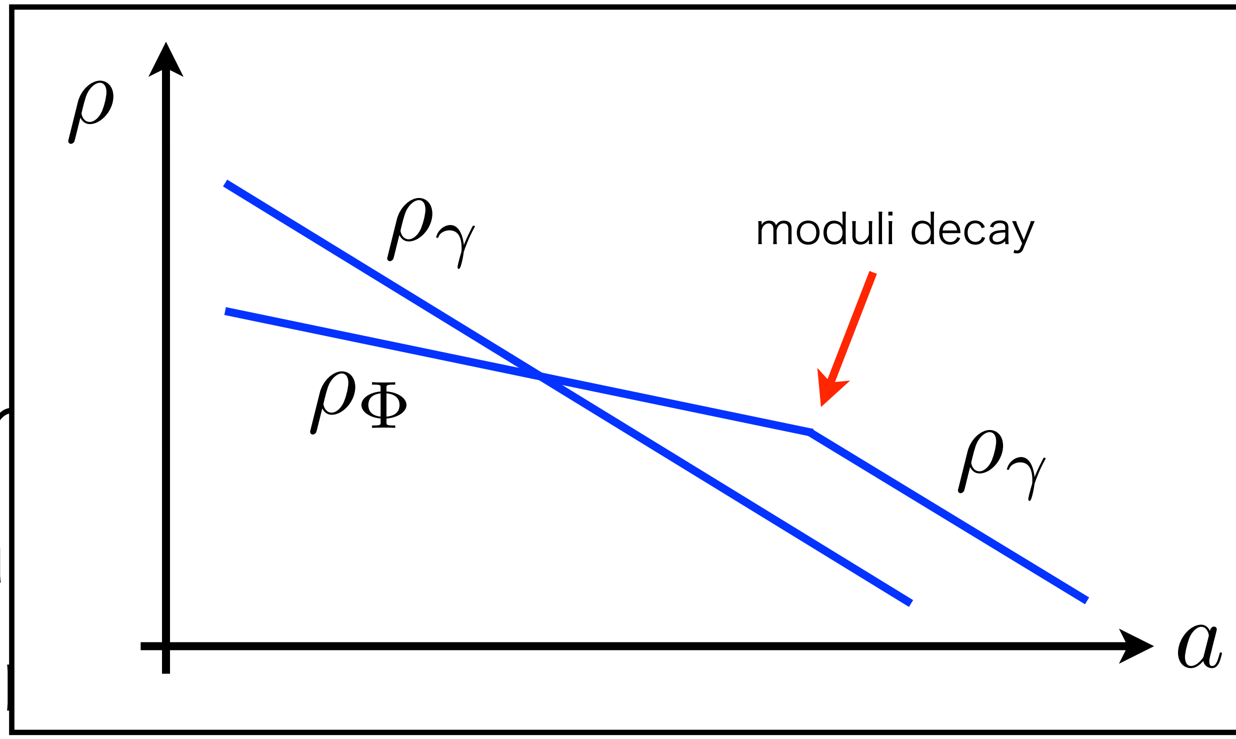


$$\rho_\Phi \propto a^{-3}$$

Our model



-Inflaton decays ... gauge interaction.

-SUSY-breaking ... uli fields are as

heavy as inflator ... $h_Z > h_Y$.

-moduli field sta ... g vacuum during

inflation and sta ...

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

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

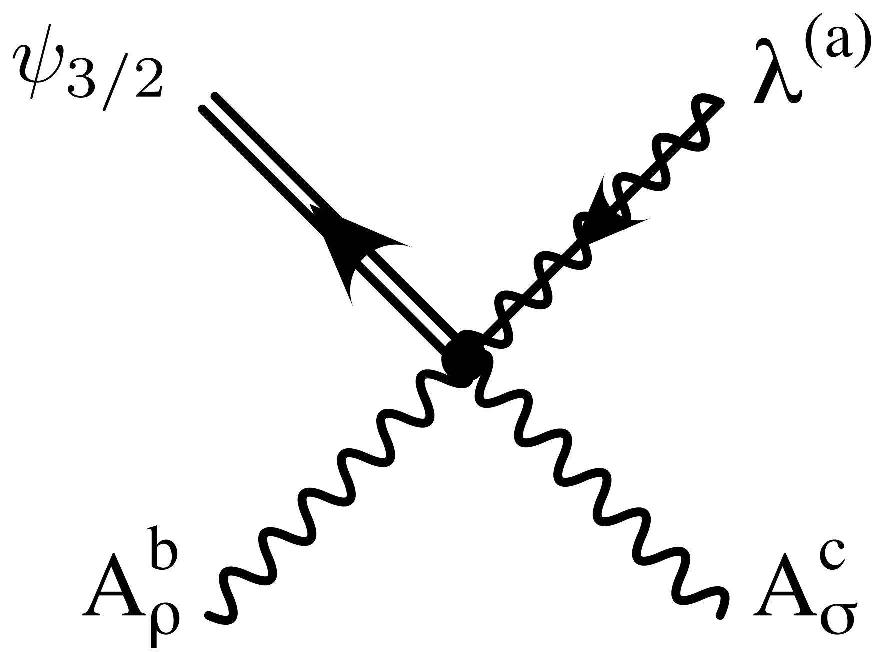
$$T_{\rm d} \simeq 4.4\,{\rm MeV} \times \left(\frac{m_{\tilde g}}{3.5 m_{\tilde e}}\right)^{-2} \left(\frac{m_{\tilde g}}{1.5\,{\rm TeV}}\right)^{3} \left(\frac{m_{3/2}}{15\,{\rm GeV}}\right)^{-1} \left(\frac{m_{\Phi}}{300\,{\rm GeV}}\right)^{-1/2} .$$

⇒ Gravitinos can be dark matter !

Gravitino production mechanism

✓ gluino scattering in the thermal plasma

'05 Kawasaki Kohri and Moroi



⇒ effective at reheating

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

can be diluted by the moduli decay

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

✓ moduli decay '07 Ibe and Kitano

$$\Phi \to \psi_{3/2}\psi_{3/2}$$

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

Constraints on the model

✓ amplitude of primordial perturbation

⇨ $\mathcal{P}_{\mathcal{R}}^{1/2} \simeq 4.9 \times 10^{-5}$

✓ moduli must decay before BBN

⇨ $T_d \gtrsim 2\mathrm{MeV}$

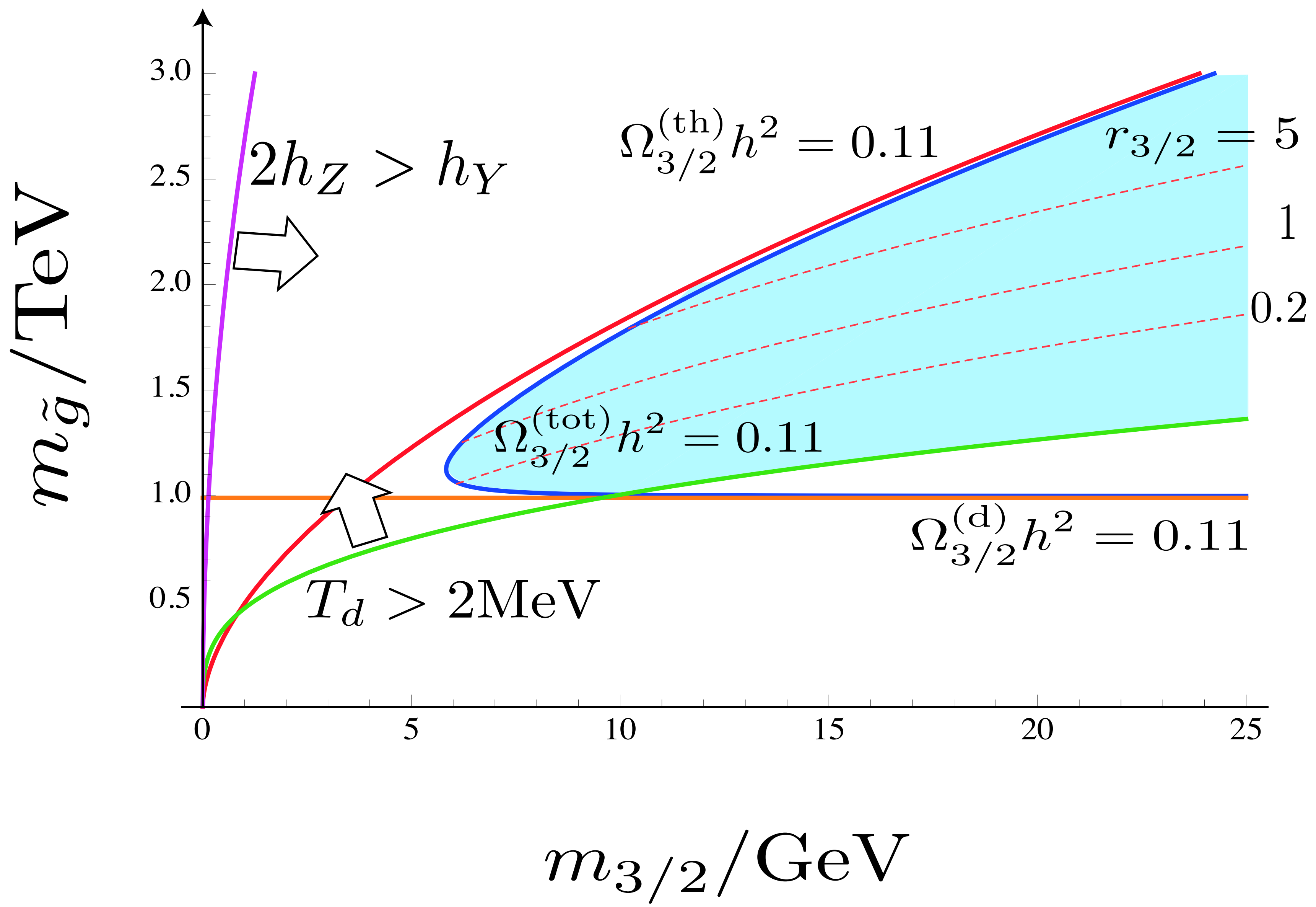
✓ Gravitinos must not overclose the Universe

⇨ $\Omega_{3/2} h^2 \lesssim 0.11$

These conditions determine
the allowed parameter region

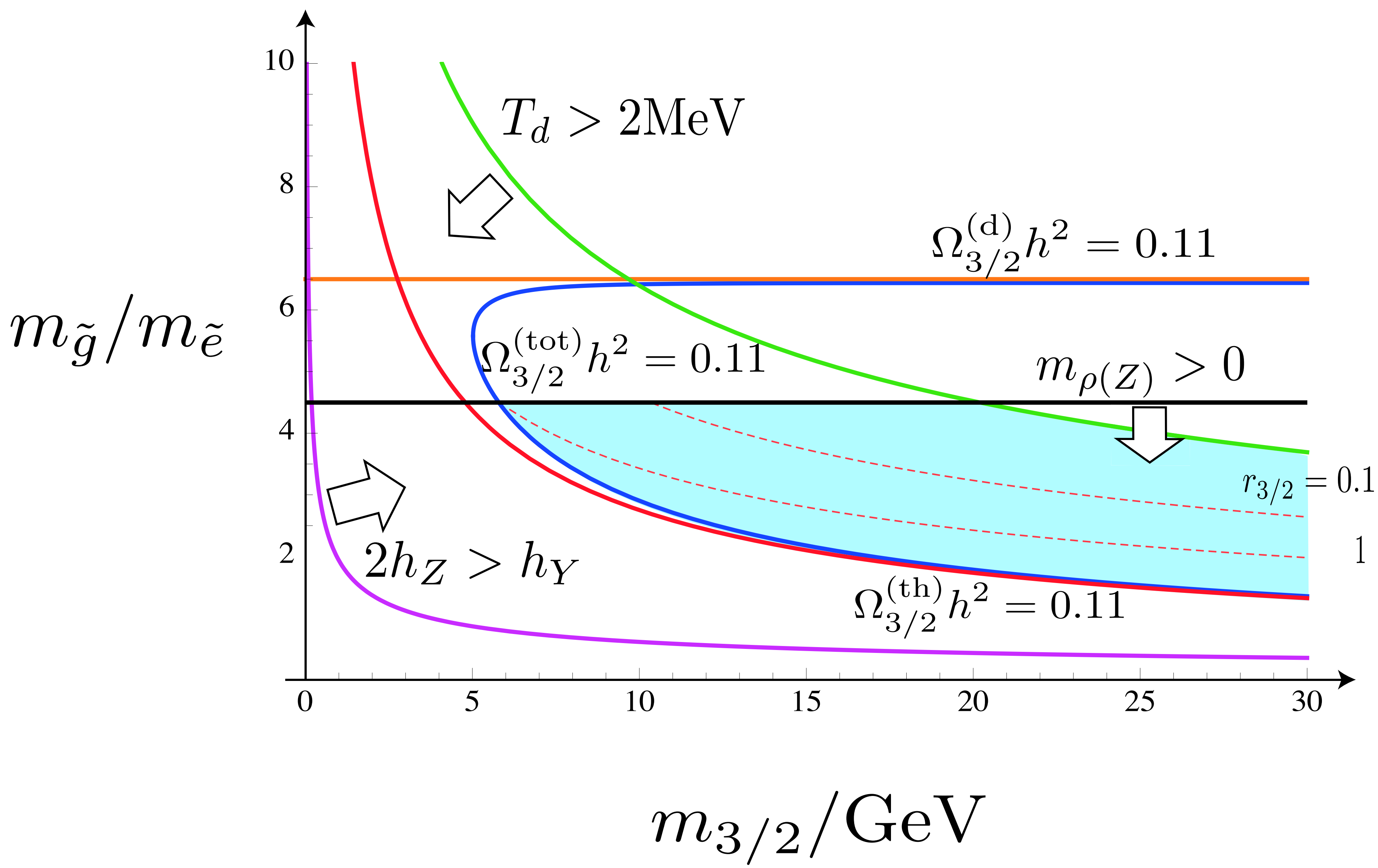
Allowed parameter region

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



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, smooth hybrid inflation

-baryogenesis → Affleck-Dine mechanism?

new baryogenesis mechanism associated with SUSY-breaking sector

Appendix

-gauge mediation

⇒ No Flavor Changing Neutral Current Problem

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

-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 !

soft mass parameters

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

gaugino/scalar mass

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

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

$$\Downarrow$$

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

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

moduli parameters

Effective Kahler

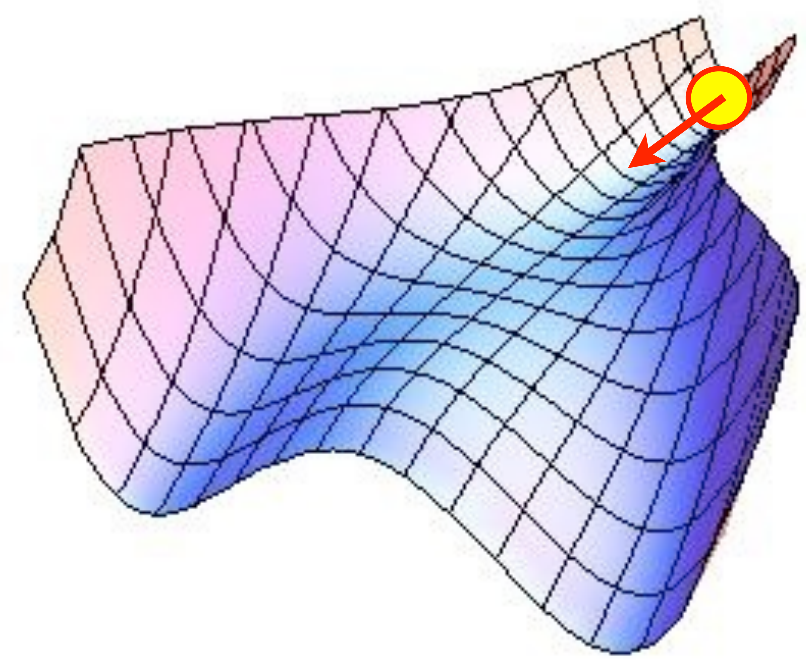
$$K_{\text{eff}} \simeq |\Phi|^2 - \frac{N}{32\pi^2}\left[h_\Phi m_{\text{Z}}\left(\Phi+\Phi^\dagger\right) + h_\Phi^2|\Phi|^2 \right.$$
$$\left. - \frac{1}{8}\frac{h_{\text{Y}}h_\Phi^3}{h_{\text{Z}}^2}\frac{m_{\text{Z}}}{m^2}|\Phi|^2\left(\Phi+\Phi^\dagger\right) + \frac{1}{8}\frac{h_{\text{Y}}h_\Phi^4}{h_{\text{Z}}^2}\frac{1}{m^2}|\Phi|^4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

@meta stable vacuum

$$|\Phi_0| \simeq \frac{1}{2}\frac{m_{\text{Z}}}{h_\Phi}, \quad \arg\Phi_0 = 0,$$
$$m_\Phi^2 \simeq \frac{N}{64\pi^2}\frac{h_{\text{Y}}h_\Phi^4}{h_{\text{Z}}^2}\frac{\mu^4}{m^2} \equiv m_{\text{CW}}^2.$$

Cosmic history

Hybrid inflation
in the SUSY-breaking sector



Cosmic history

Hybrid inflation
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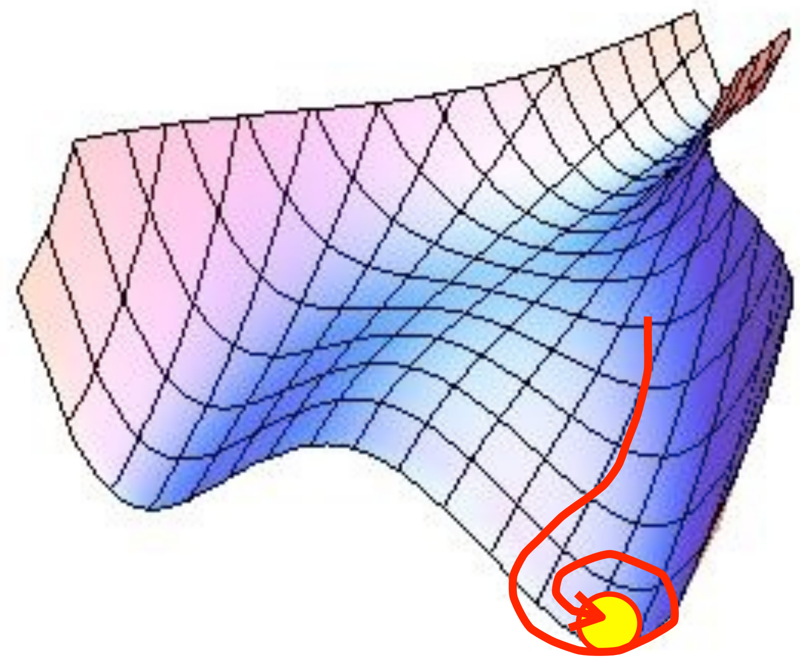
Inflaton and waterfall fields
oscillate around
the potential minimum



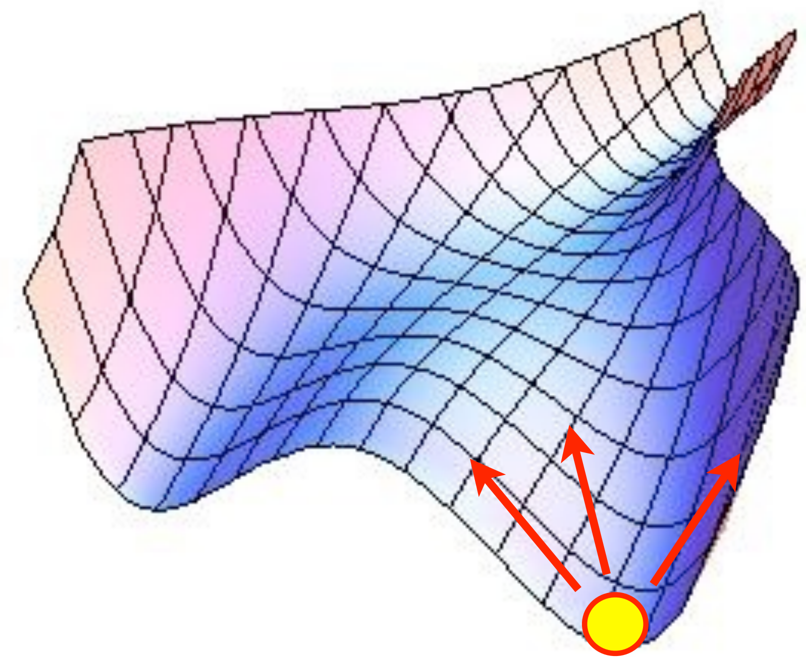
Cosmic history

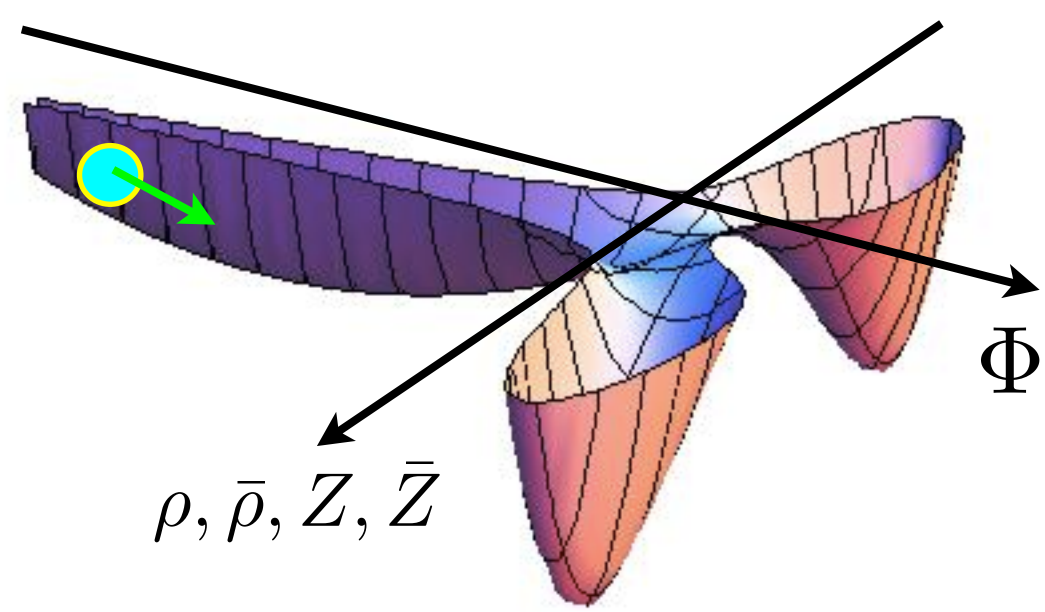
Hybrid inflation
in the SUSY-breaking sector

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
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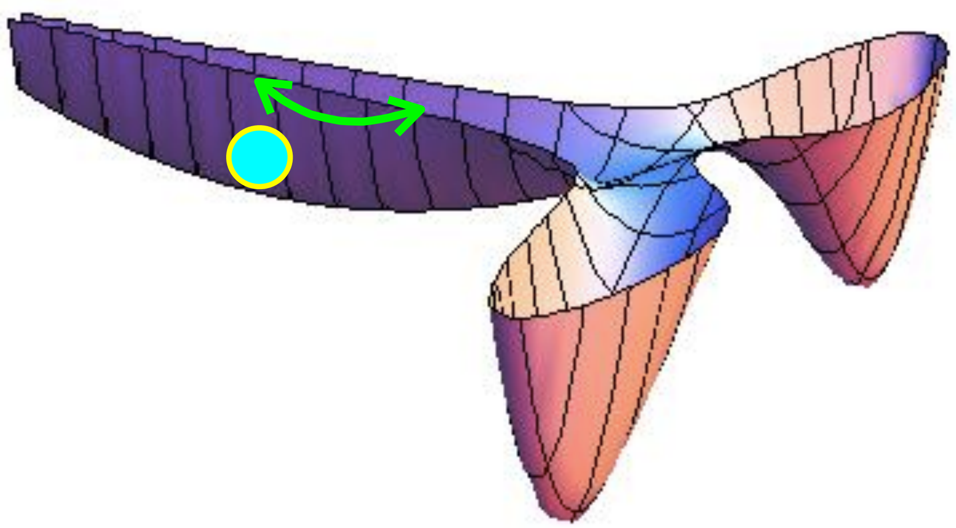


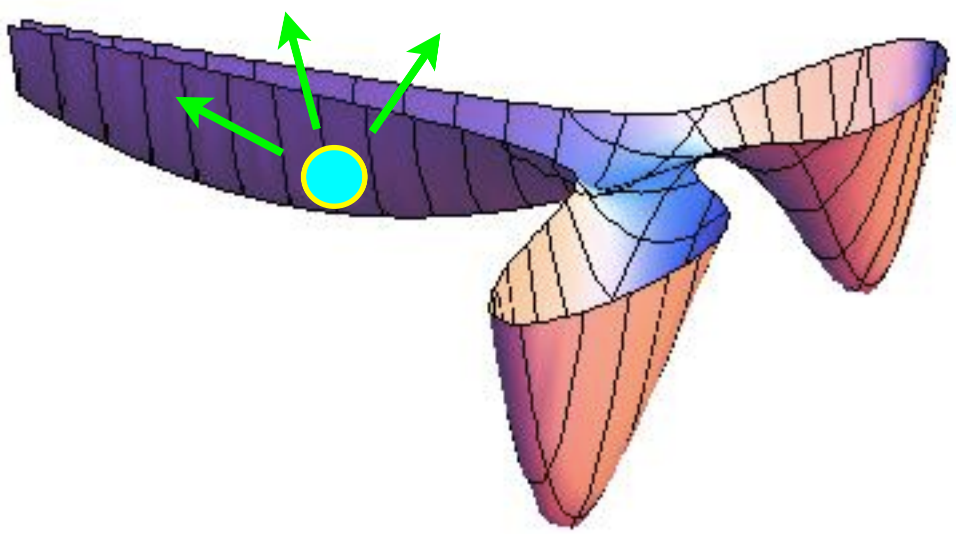
gravitino production/
moduli starts oscillation

(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



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Cosmic history

Hybrid inflation
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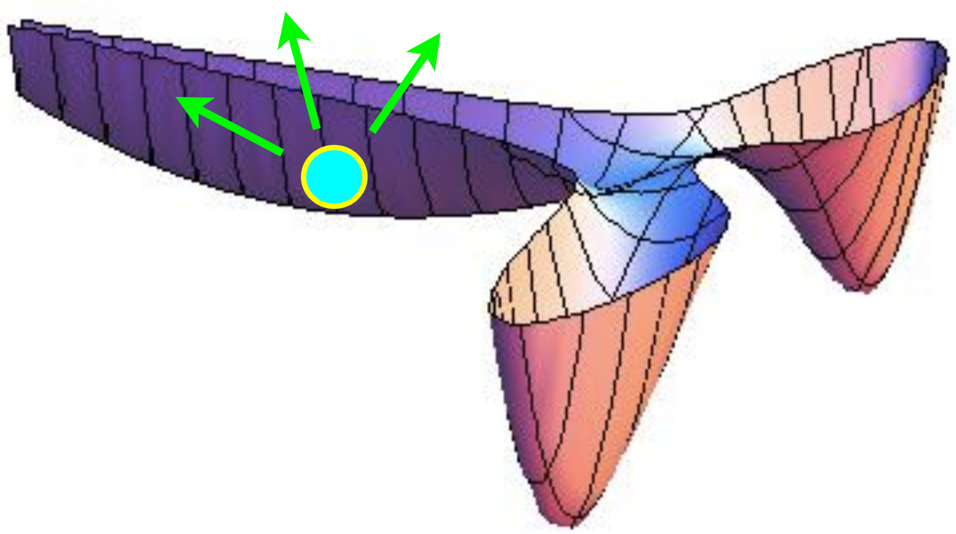

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moduli oscillation (may) dominate
the energy density of the Universe

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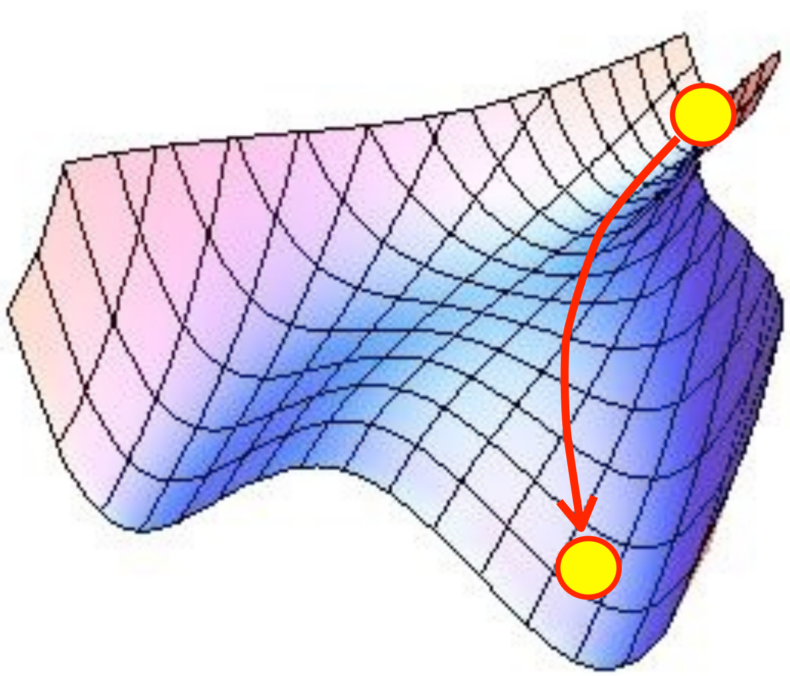
Precise reheating
temperature
Gravitino Dark Matter

testable prediction

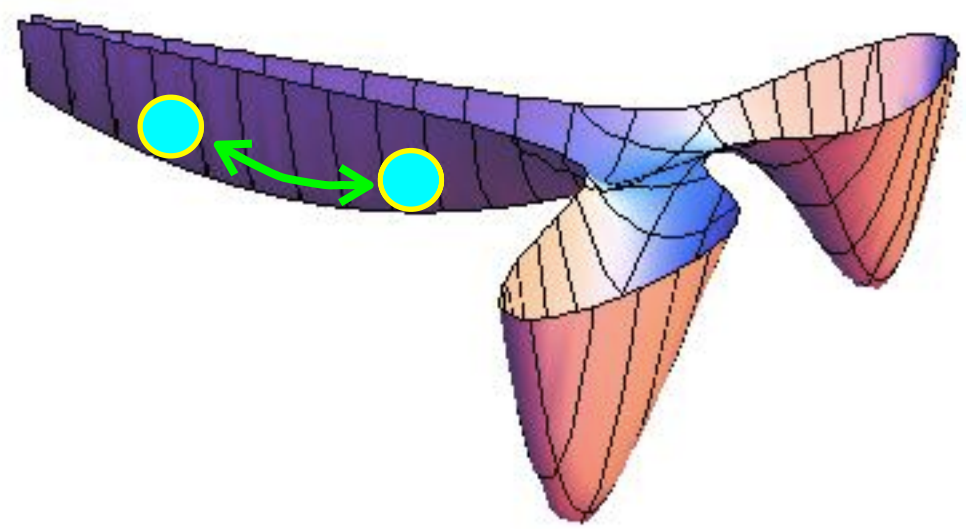
Our model

✓ 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 !!