Moduli cosmology

The 3rd UTQuest workshop ExDiP 2012
at Obihiro, 2012 Aug. 7

Fumi Takahashi
(Tohoku Univ.)

In this talk, I would like to revisit the cosmological moduli problem (CMP).

In this talk, I would like to revisit the cosmological moduli problem (CMP).

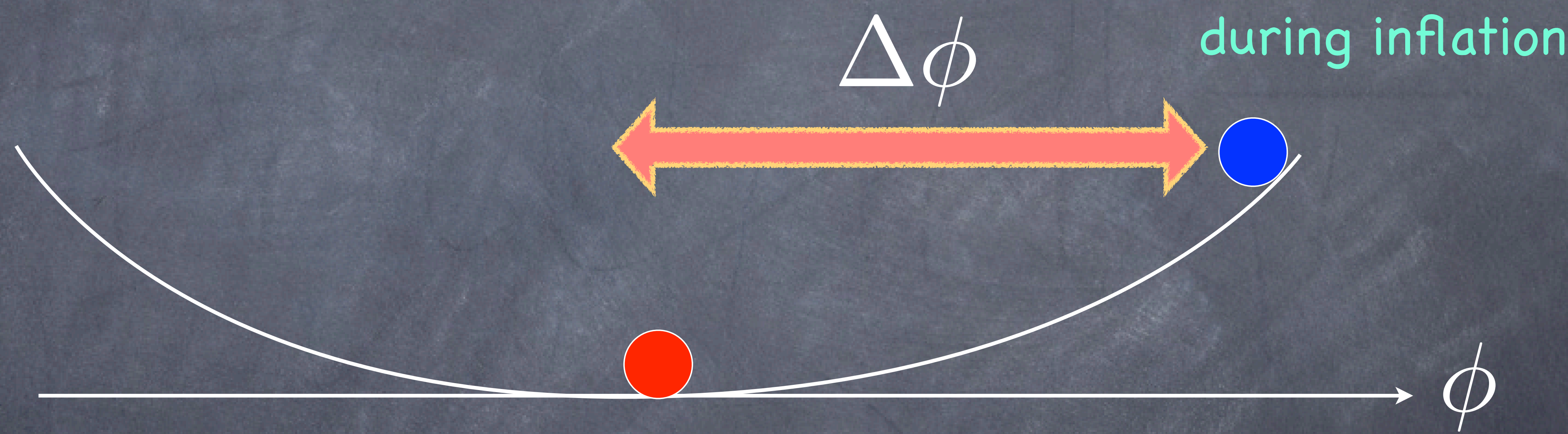
What's CMP?

Why now?

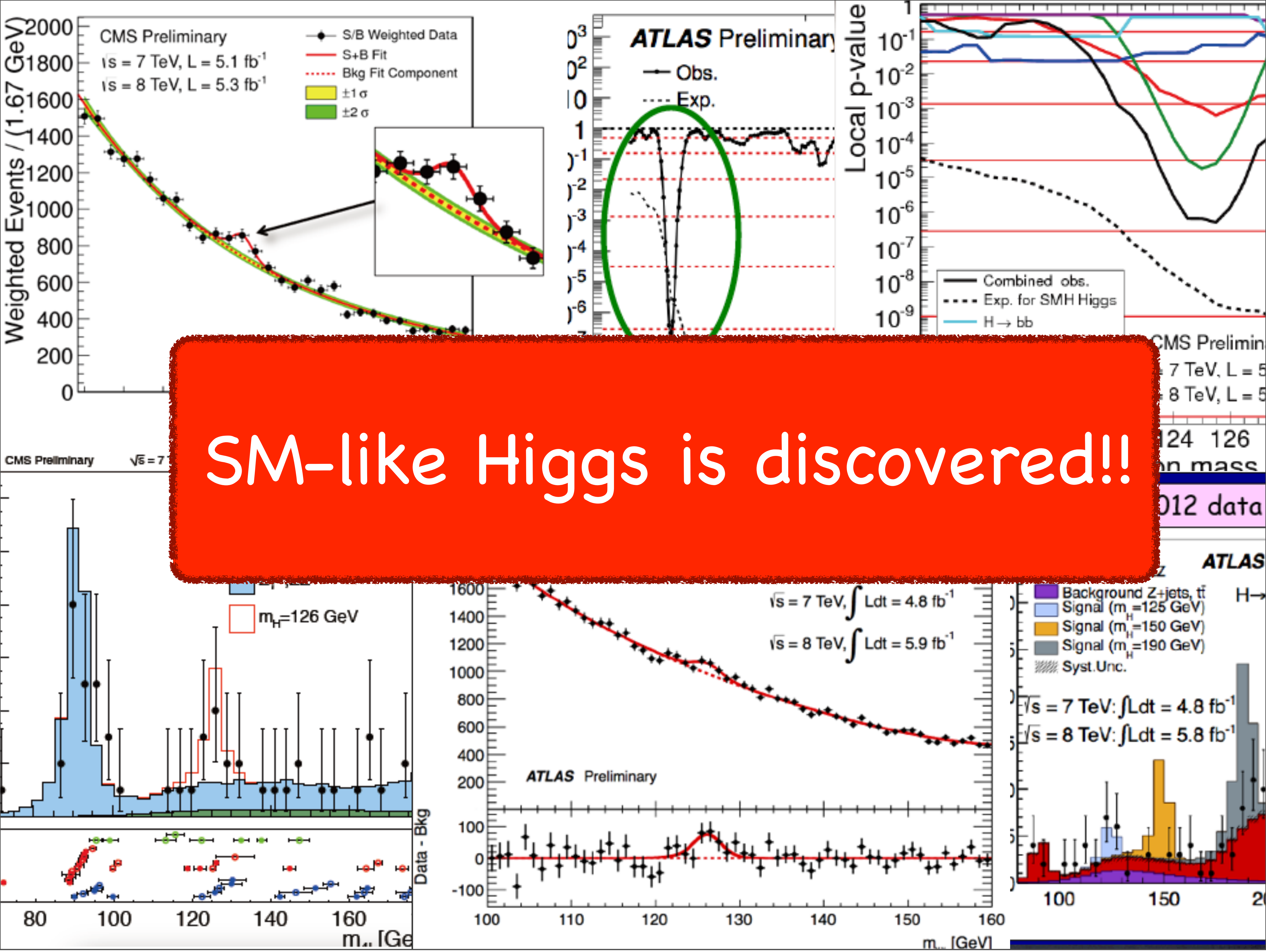
Cosmological moduli problem

G. D. Coughlan et al (1983)

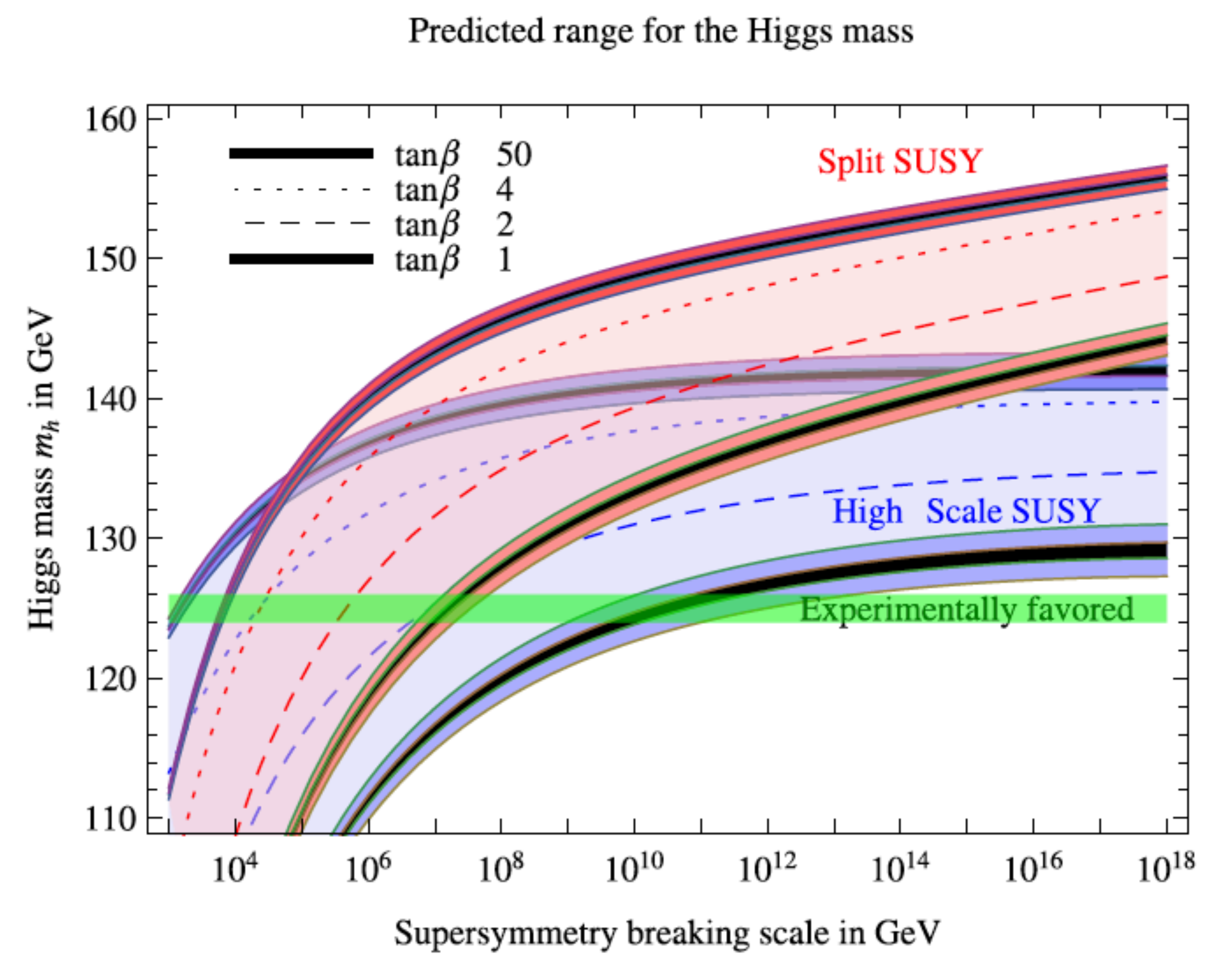
ϕ : light modulus field



The moduli dominate the Universe and decay late, spoiling the success of BBN. Even if they decay before BBN, the baryon asymmetry will be diluted.


SM-like Higgs is discovered!!
CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
ATLAS Preliminary
Obs.
Exp.
Local p-value
Combined obs.
Exp. for SMH Higgs
H → bb
m_H=126 GeV
√s = 7 TeV, ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV, ∫Ldt = 5.9 fb⁻¹
Data - Bkg
ATLAS
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹

10-10^{4}TeV SUSY?



G.F. Giudice, A. Strumia / Nuclear Physics B 858 (2012) 63–83

10-10^4TeV SUSY?

- The 125GeV Higgs mass suggests high-scale SUSY breaking at, say, 10-10^4TeV.
- The cosmological moduli problem will be greatly relaxed, and successful moduli cosmology may be possible.
- The moduli problem may provide a probe of high-energy physics and the early Universe.
- So, let us revisit the moduli problem.

What are the key ingredients?

1) Initial deviation from the low-energy minimum during inflation.

2) Coherent oscillations after inflation.

3) Decay into light degrees of freedom.

1) and 2) determine the moduli abundance.

The cosmological impact depends on 3)

What are the key variables?

The moduli dynamics depends on

1) if the Hubble-induced correction exists

2) if the inflation scale is larger than the modulus mass

The moduli decay depends on the mass spectrum, how it is stabilized, how SUSY is broken, etc.

$$H_{\rm inf}\,,\, m_\phi\,,\, m_{3/2}\,,\, m_I\,,\, c\ \ \cdots$$

Contents

- Moduli abundance
- Adiabatic suppression mechanism
- Moduli-induced gravitino problem
- Baryogenesis
- Moduli curvaton

Moduli abundance (1)

Initial deviation

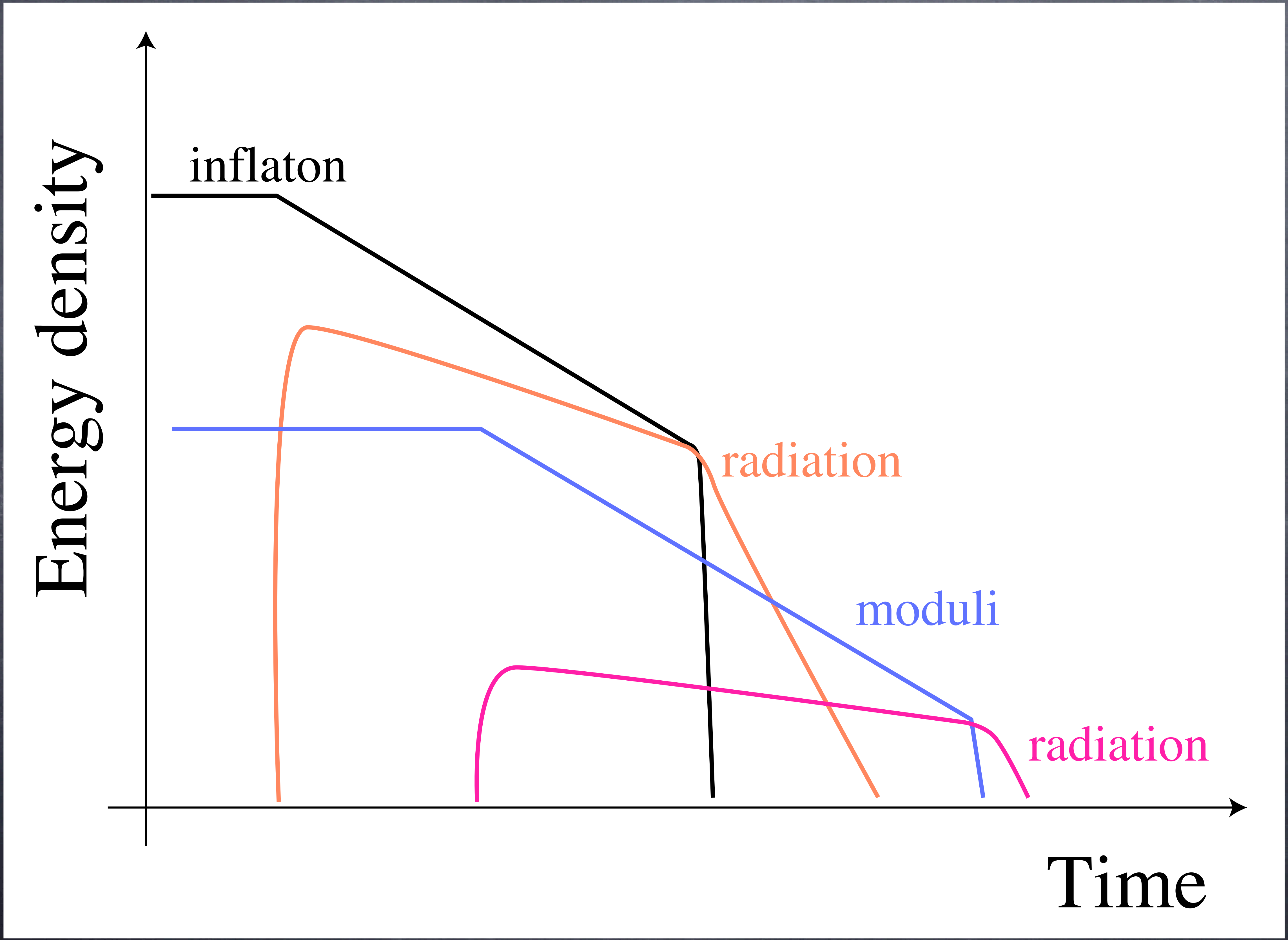
Simplifying assumptions

- The typical scale of the moduli is given by the Planck scale, $M_p = 2.4 \times 10^{18}$ GeV.
- The initial position is not close to special points such as local extrema.

It is trivial to change the typical scale.

If the moduli sits close to a local maximum, the moduli domination is more likely.

Thermal history



2012年8月7日火曜日

Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction		
w/ Hubble correction		

Case analysis

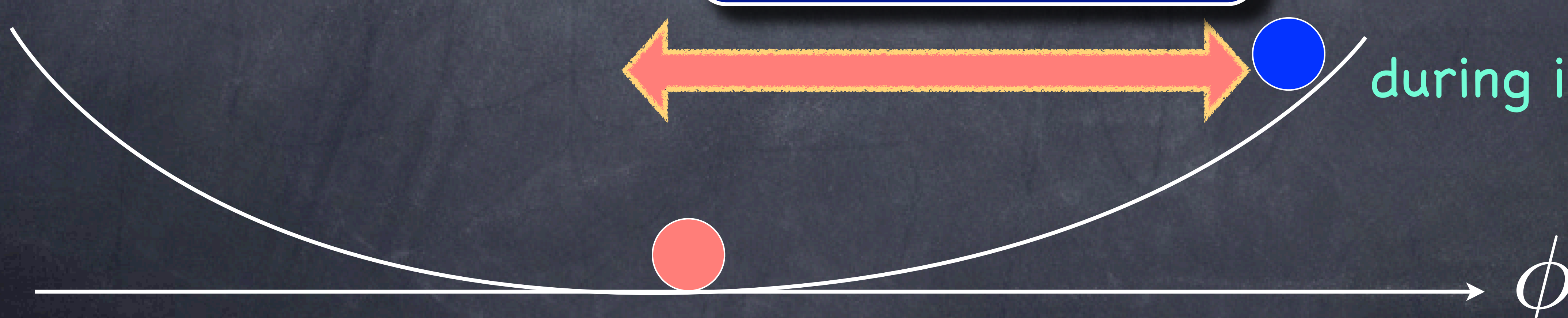
	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction		
w/ Hubble correction		

Suppose that the moduli does not receive any Hubble-correction during inflation due to e.g. a shift symmetry.

If $H_{\rm inf} \gtrsim m_\phi$

the initial position is deviated from the min. by accumulation of quantum fluctuations.

$$\boxed{\Delta\phi \sim M_p}$$

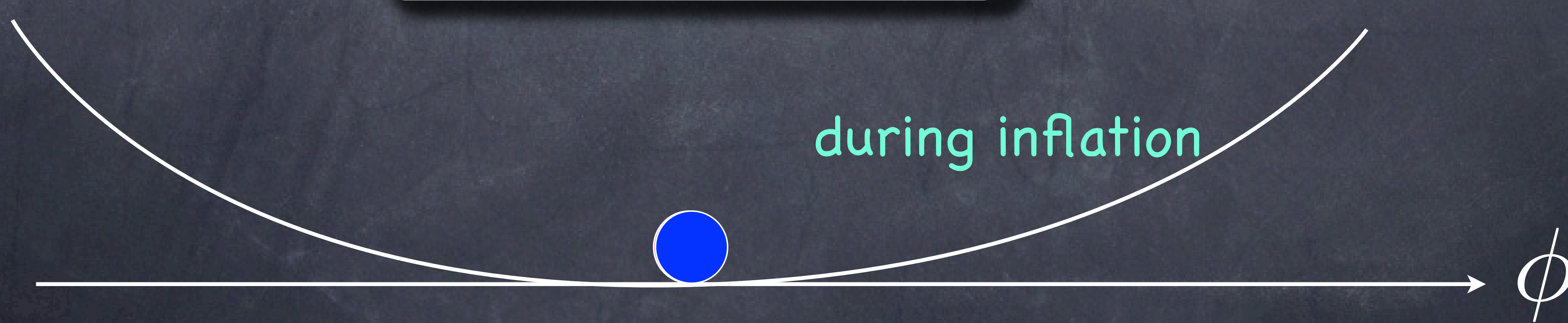


Suppose that the moduli does not receive any Hubble-correction during inflation due to e.g. a shift symmetry.

If $H_{\rm inf} \lesssim m_\phi$

the moduli settles down at the minimum during inflation.

$$\Delta\phi \sim 0$$



Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\Delta\phi \sim M_p$	$\Delta\phi \sim 0$
w/ Hubble correction		

Case analysis

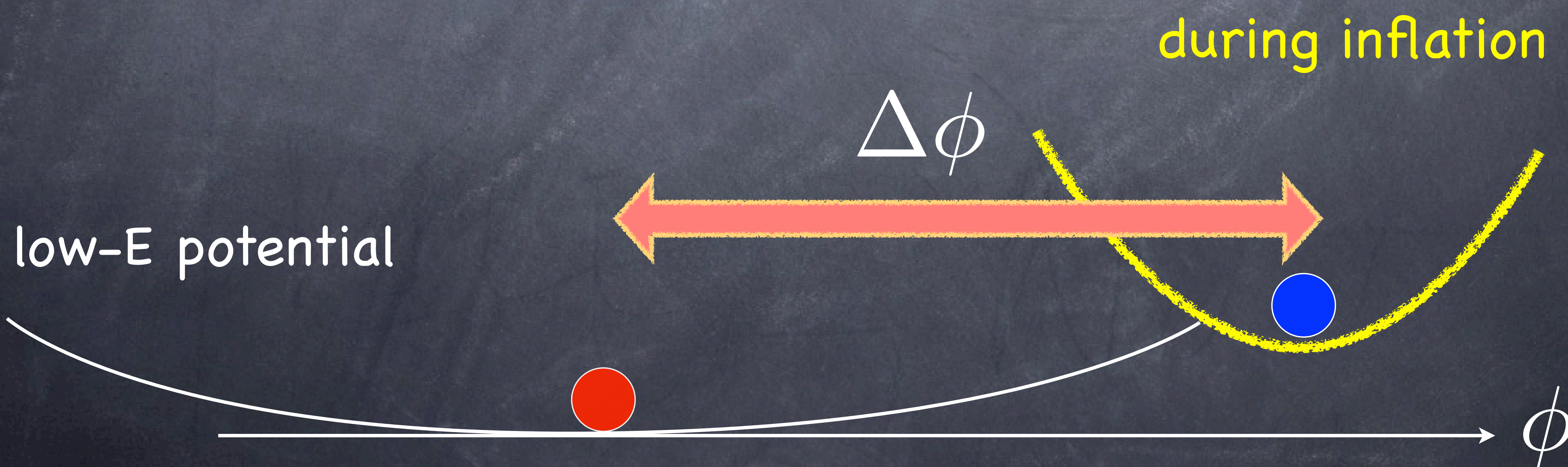
	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\Delta\phi \sim M_p$	$\Delta\phi \sim 0$
w/ Hubble correction		

Suppose that the moduli mass receives Hubble-correction during inflation, thru Planck suppressed interactions.

A toy model:

$$V = \frac{1}{2} m_\phi^2 \phi^2 + \frac{c^2}{2} H_{\rm inf}^2 (\phi - M_p)^2$$

We assume $c \sim O(1)$ for the moment.



If $H_{\rm inf} \gtrsim m_\phi$

$$\boxed{\Delta\phi \sim M_p}$$

If $H_{\rm inf} \lesssim m_\phi$

$$\boxed{\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p}$$

This is considered to be the case if $H_{\rm inf}$ is bounded above to avoid run-away and decompactification.

Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\Delta\phi \sim M_p$	$\Delta\phi \sim 0$
w/ Hubble correction	$\Delta\phi \sim M_p$	$\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p$

N.B. This is just initial deviation. The moduli abundance depends on the moduli dynamics after inflation.

Moduli abundance (2)

Coherent oscillations

Let us estimate the moduli abundance.

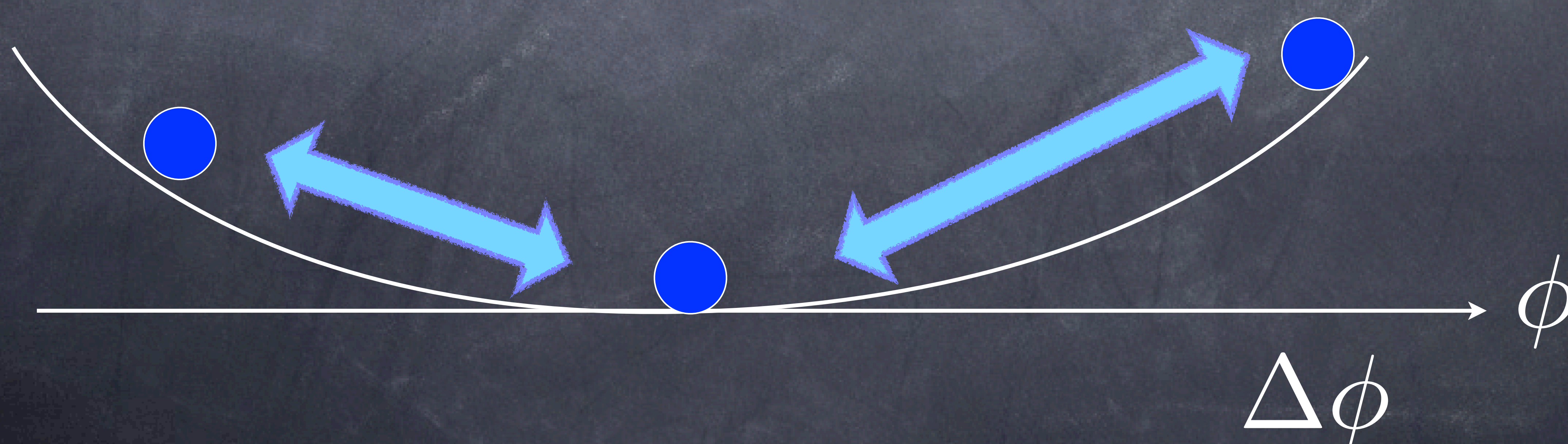
If $H_{\rm inf} \gtrsim m_\phi$, the moduli starts coherent oscillations when $H_{\rm inf} \sim m_\phi$ after inflation.

$$\frac{\rho_\phi}{s} = \left.\frac{\rho_I}{s}\right|_R \left.\frac{\rho_\phi}{\rho_I}\right|_{\rm osc} = \frac{3T_R}{4}\frac{\frac{1}{2}m_\phi^2\Delta\phi^2}{3m_\phi^2 M_p^2}$$

$$= \frac{1}{8}T_R\left(\frac{\Delta\phi}{M_p}\right)^2$$

entropy from inflaton

If higher than Td, the moduli domination.



Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\Delta\phi \sim M_p$	$\Delta\phi \sim 0$
w/ Hubble correction	$\Delta\phi \sim M_p$	$\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p$

Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\frac{\rho_\phi}{s} \sim 0.1\, T_R$	$\frac{\rho_\phi}{s} \sim 0$
w/ Hubble correction	$\frac{\rho_\phi}{s} \sim 0.1\, T_R$	$\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p$

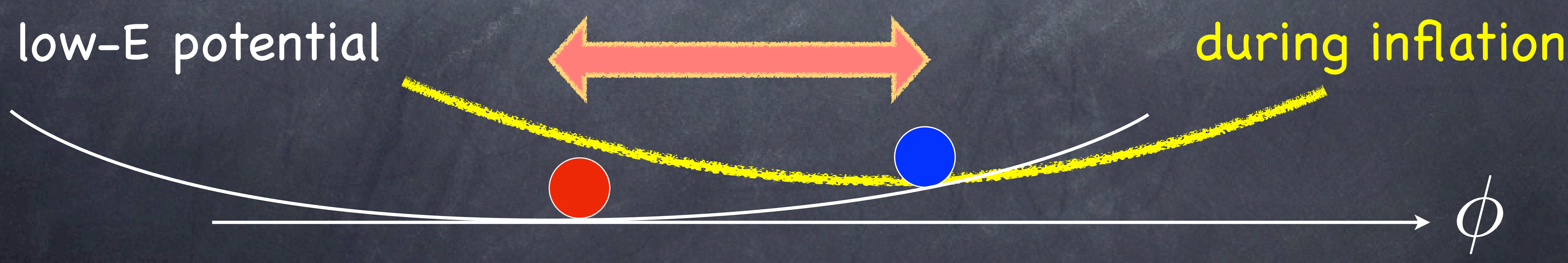
Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\frac{\rho_\phi}{s} \sim 0.1\, T_R$	$\frac{\rho_\phi}{s} \sim 0$
w/ Hubble correction	$\frac{\rho_\phi}{s} \sim 0.1\, T_R$	$\boxed{\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p}$

Suppose that the moduli mass receives Hubble-correction during inflation, and $H_{\rm inf} \lesssim m_\phi$.

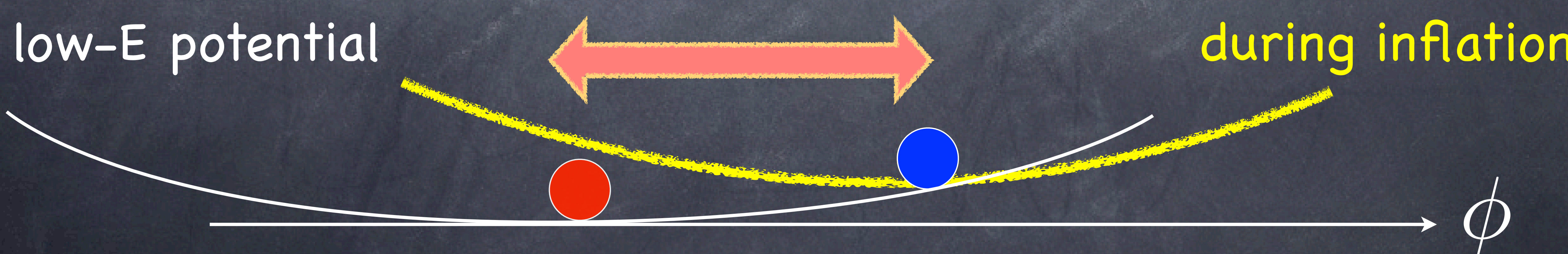
Whether the coherent oscillations are induced depends on how the Hubble correction changes with time.

$$\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p$$



If (in an extreme case) the Hubble correction disappears instantly after inflation, the coherent oscillations are induced with an amplitude $\Delta\phi$.

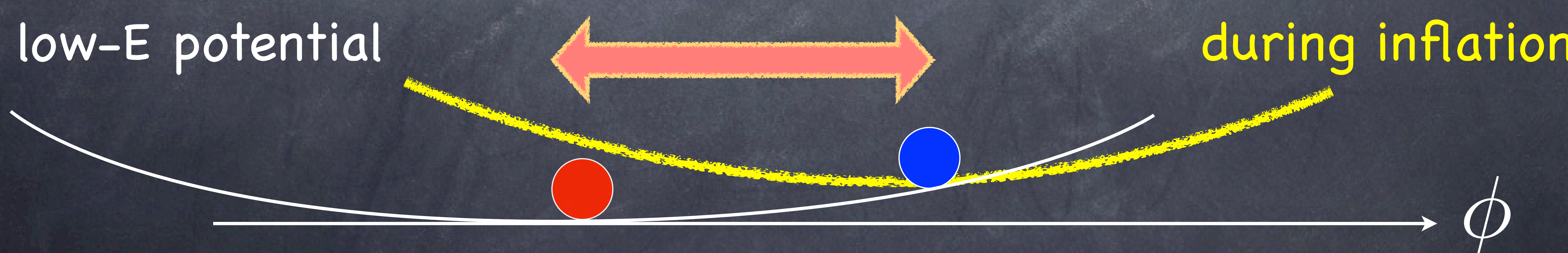
$$\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p$$



On the other hand, if the Hubble correction changes slowly with time, compared with the modulus mass, no coherent oscillations are produced.

This is because the number density is conserved as it is the adiabatic invariant.

$$\Delta\phi \sim \left(\frac{H_{\rm inf}}{m_\phi}\right)^2 M_p$$



The typical time scale of the change of the Hubble correction is determined by the inflaton mass, m_I.

The Hubble-induced mass originates from here.

$$\mathcal{L} = |\partial I|^2 - e^K (D_i W K^{i\bar{j}} D_{\bar{j}} W^\dagger - 3|W|^2)$$

After inflation, the inflaton starts to oscillate, and the inflaton potential energy first goes to the kinetic energy in a time scale of m_I^{-1}.

To summarize,

$$\frac{\rho_\phi}{s} \sim \begin{cases} \dfrac{1}{8} T_R \left(\dfrac{H_{\rm inf}}{m_\phi}\right)^4 & \text{for} \quad m_I > m_\phi \\[2em] 0 & \text{for} \quad m_I < m_\phi \end{cases}$$

The inflaton mass is important for the moduli problem.

Kamada, Higaki, FT, 1207.2771

cf. Nakayama, FT, Yanagida 1109.2073

Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\dfrac{\rho_\phi}{s} \sim 0.1\, T_R$	$\dfrac{\rho_\phi}{s} \sim 0$
w/ Hubble correction	$\dfrac{\rho_\phi}{s} \sim 0.1\, T_R$	$\dfrac{\rho_\phi}{s} \sim \begin{cases} 0.1\, T_R \left(\dfrac{H_{\rm inf}}{m_\phi}\right)^4 & \text{for} \quad m_I > m_\phi \\ 0 & \text{for} \quad m_I < m_\phi \end{cases}$

Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\dfrac{\rho_\phi}{s} \sim 0.1\,T_R$	$\dfrac{\rho_\phi}{s} \sim 0$
w/ Hubble correction	$\dfrac{\rho_\phi}{s} \sim 0.1\,T_R$	$\dfrac{\rho_\phi}{s} \sim \begin{cases} 0.1\,T_R \left(\dfrac{H_{\rm inf}}{m_\phi}\right)^4 & \text{for} \quad m_I > m_\phi \\ 0 & \text{for} \quad m_I < m_\phi \end{cases}$

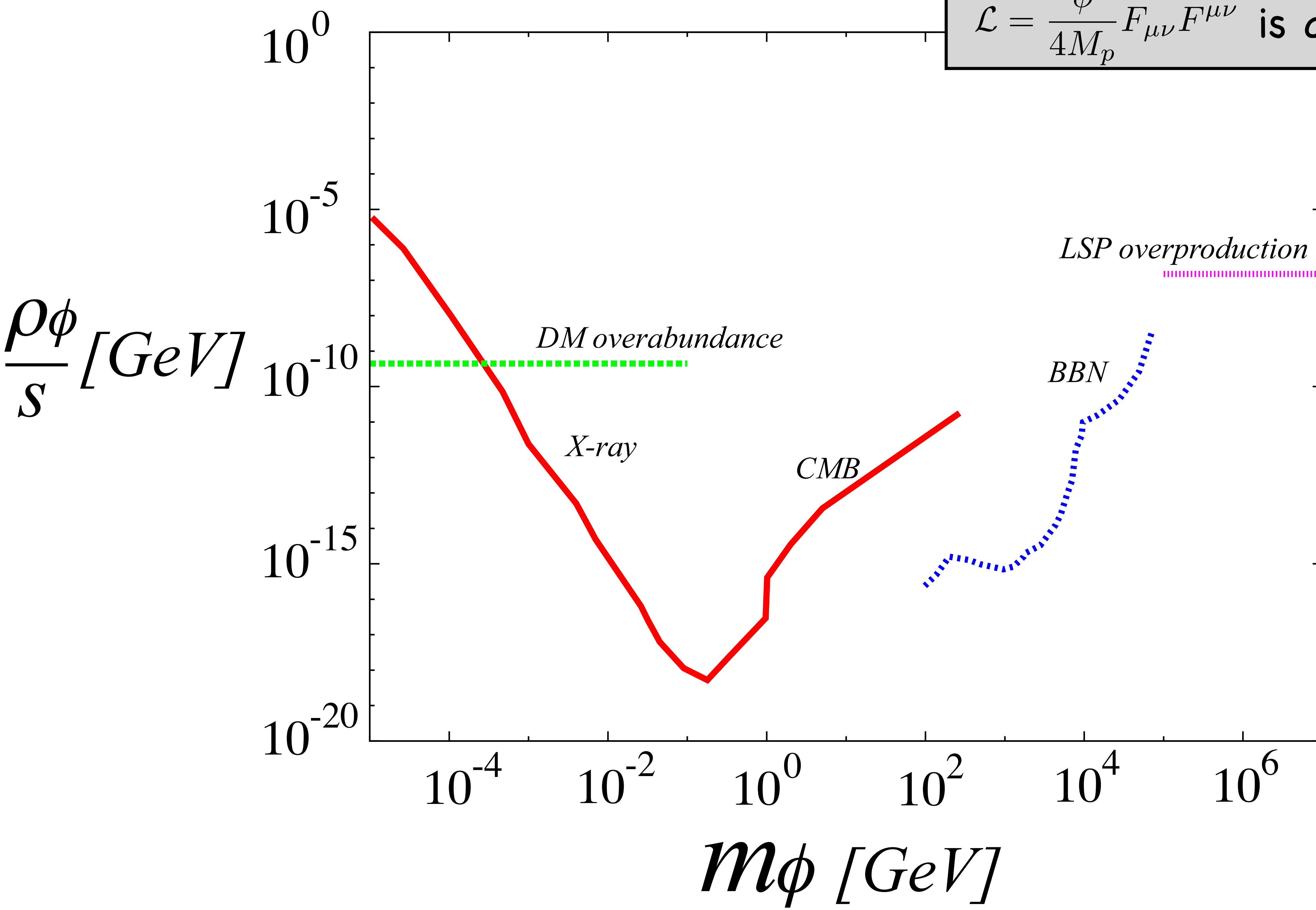
Case analysis

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\dfrac{\rho_\phi}{s} \sim 0.1\,T_R$	$\dfrac{\rho_\phi}{s} \sim 0$
w/ Hubble correction	$\dfrac{\rho_\phi}{s} \sim 0.1\,T_R$	$\dfrac{\rho_\phi}{s} \sim \begin{cases} 0.1\,T_R \left(\dfrac{H_{\rm inf}}{m_\phi}\right)^4 & \text{for } m_I > m_\phi \\ 0 & \text{for } m_I < m_\phi \end{cases}$

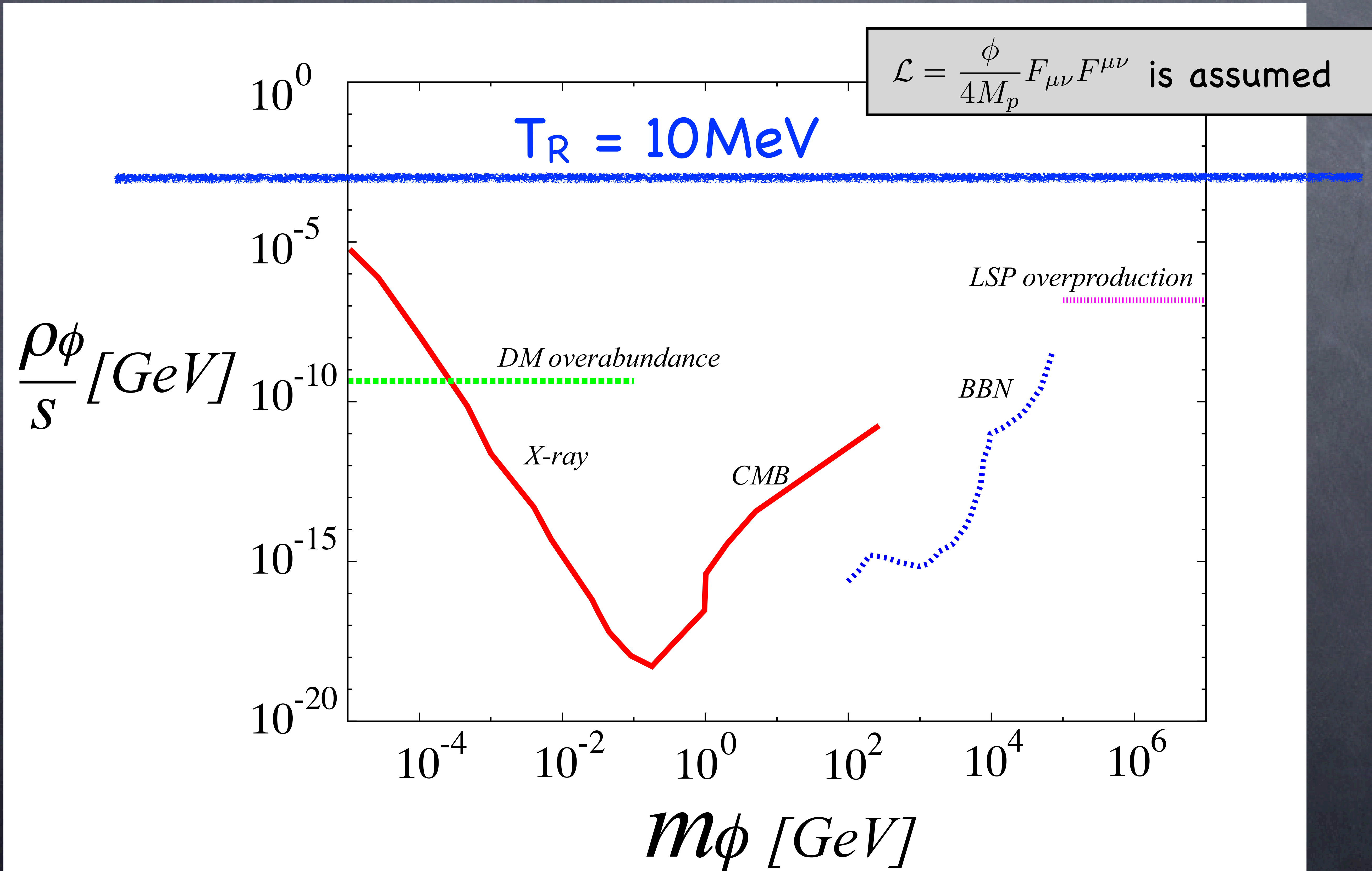
Cosmological constraints

Cosmological constraints

$\mathcal{L} = \frac{\phi}{4M_p} F_{\mu\nu} F^{\mu\nu}$ is assumed



Cosmological constraints

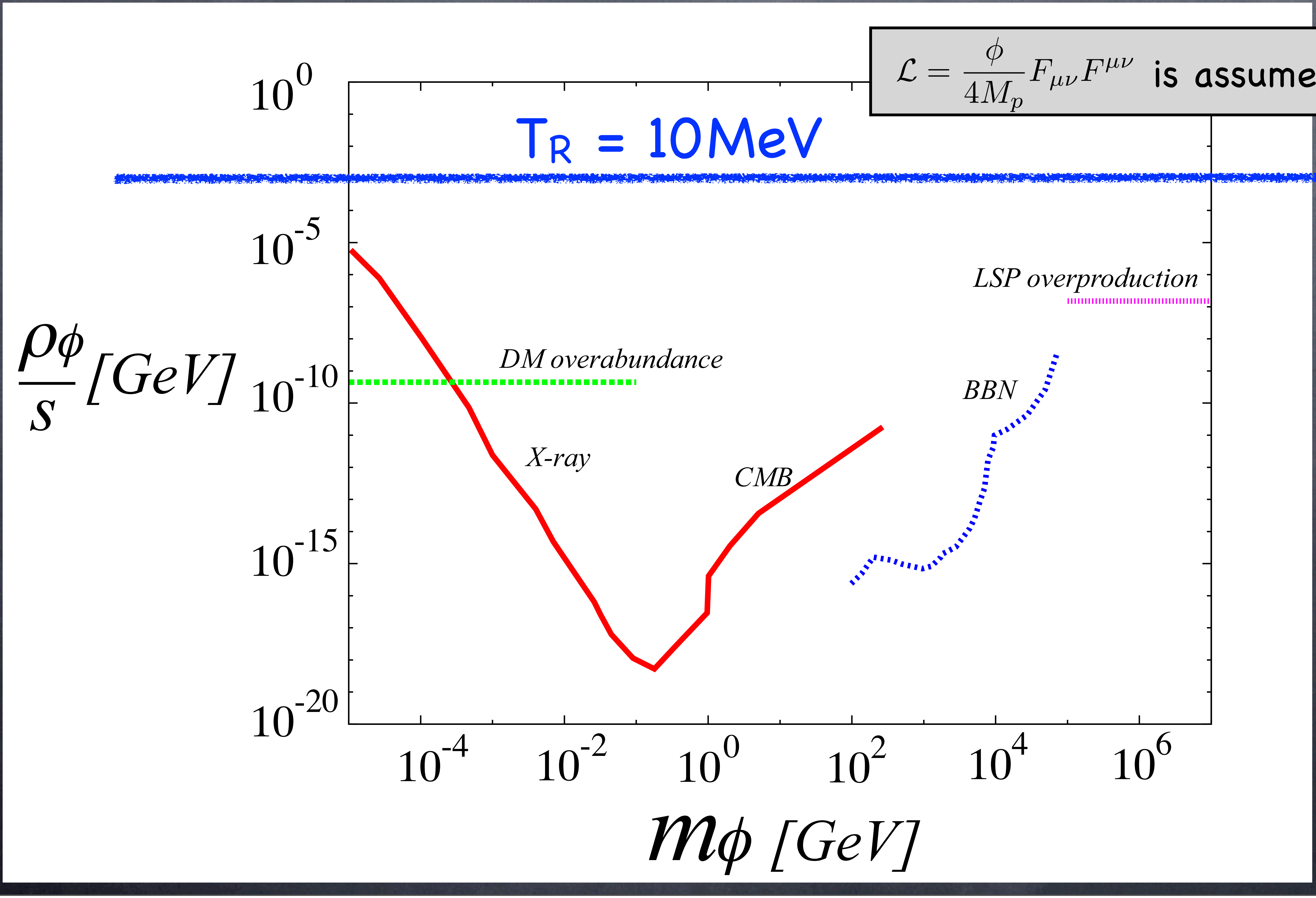


2012年8月7日火曜日

T_R = 10^9GeV

Cosmological constraints

$\mathcal{L} = \frac{\phi}{4M_p} F_{\mu\nu}F^{\mu\nu}$ is assumed



Adiabatic suppression mechanism

Linde hep-th/9601083

FT, Yanagida 1012.3227,1101.0867.

Nakayama, FT, Yanagida, 1109.2073, 1112.0418, 1203.2085

	$H_{\rm inf} \gtrsim m_\phi$	$H_{\rm inf} \lesssim m_\phi$
w/o Hubble correction	$\frac{\rho_\phi}{s} \sim 0.1\, T_R$	$\frac{\rho_\phi}{s} \sim 0$
w/ Hubble correction	$\boxed{\frac{\rho_\phi}{s} \sim 0.1\, T_R}$	$\frac{\rho_\phi}{s} \sim \begin{cases} 0.1\, T_R \left(\frac{H_{\rm inf}}{m_\phi}\right)^4 & \text{for } m_I > m_\phi \\ 0 & \text{for } m_I < m_\phi \end{cases}$

Adiabatic suppression mechanism

Linde hep-th/9601083

FT, Yanagida 1012.3227,1101.0867.

Nakayama, FT, Yanagida, 1109.2073, 1112.0418, 1203.2085

What if the Hubble-induced mass is enhanced, namely, $c \gg 1$?

Consider a toy model,

$$\boxed{V = \frac{1}{2} m_\phi^2 \phi^2 + \frac{c^2}{2} H_{\rm inf}^2 (\phi - M_*)^2}$$

Now we assume $c \gg 1$, say, $c = \mathcal{O}(10 - 10^2)$

Typical scale is changed accordingly: $M_* \sim M_p / c$

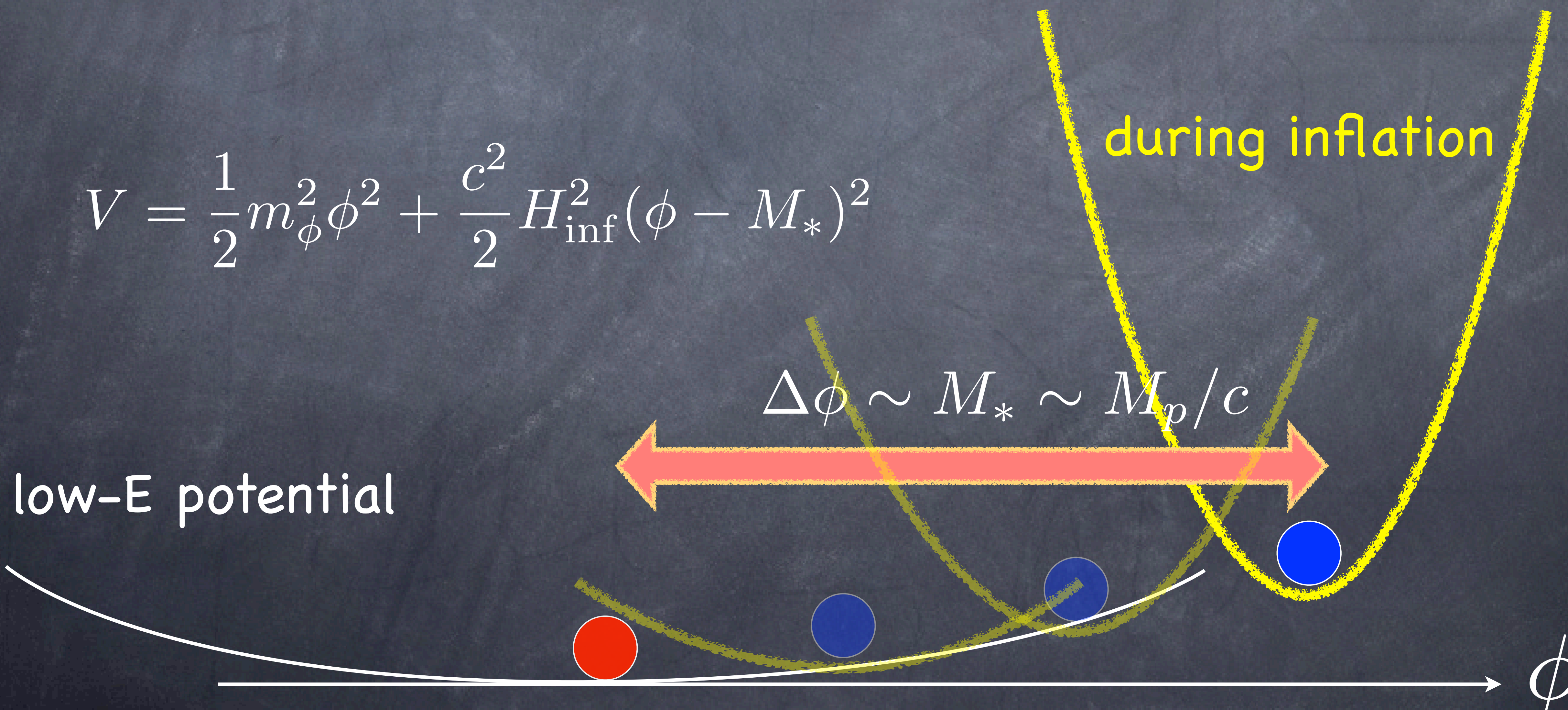
Such an enhanced coupling arises from the following quartic coupling in the Kahler potential.

$$\boxed{K \supset -\tilde{c}^2 \, |\phi|^2 |I|^2}$$

The time-dependent potential minimum is given by

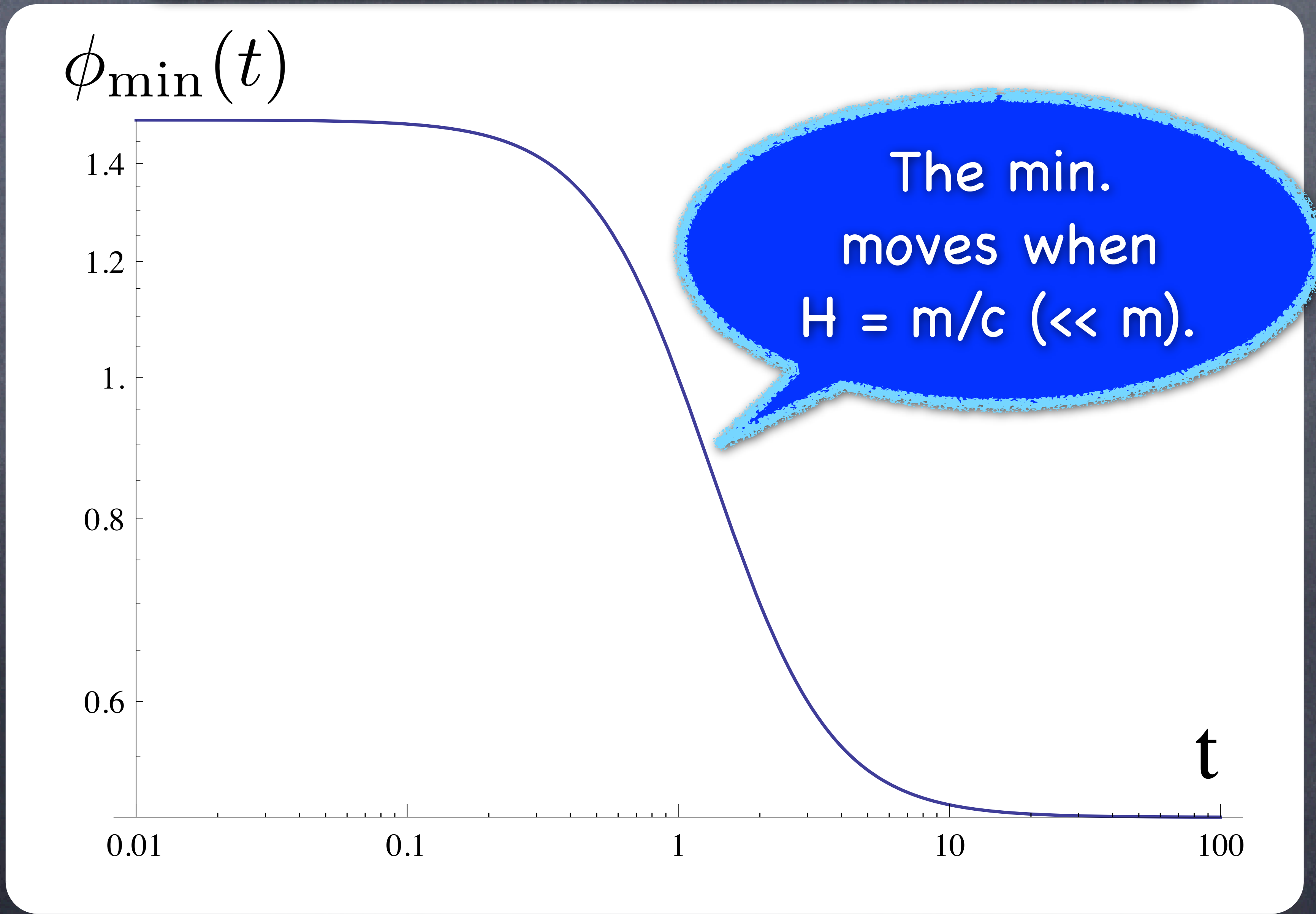
$$\boxed{\phi_{\min}(t) = \frac{c^2 H^2}{m_\phi^2 + c^2 H^2} M_*}$$

$$V = \frac{1}{2} m_\phi^2 \phi^2 + \frac{c^2}{2} H_{\rm inf}^2 (\phi - M_*)^2$$



The time-dependent potential minimum is given by

$$\phi_{\min}(t) = \frac{c^2 H^2}{m_\phi^2 + c^2 H^2} M_*$$



Since the potential changes slowly compared with the mass, the moduli follows the minimum adiabatically.

The final oscillation amplitude is exponentially suppressed by a factor of

$$\mathcal{S} = \frac{3\sqrt{2p\pi}}{4} c^{(3p+1)/2} \exp\left(-\frac{cp\pi}{2}\right), \qquad a(t) \propto t^p$$

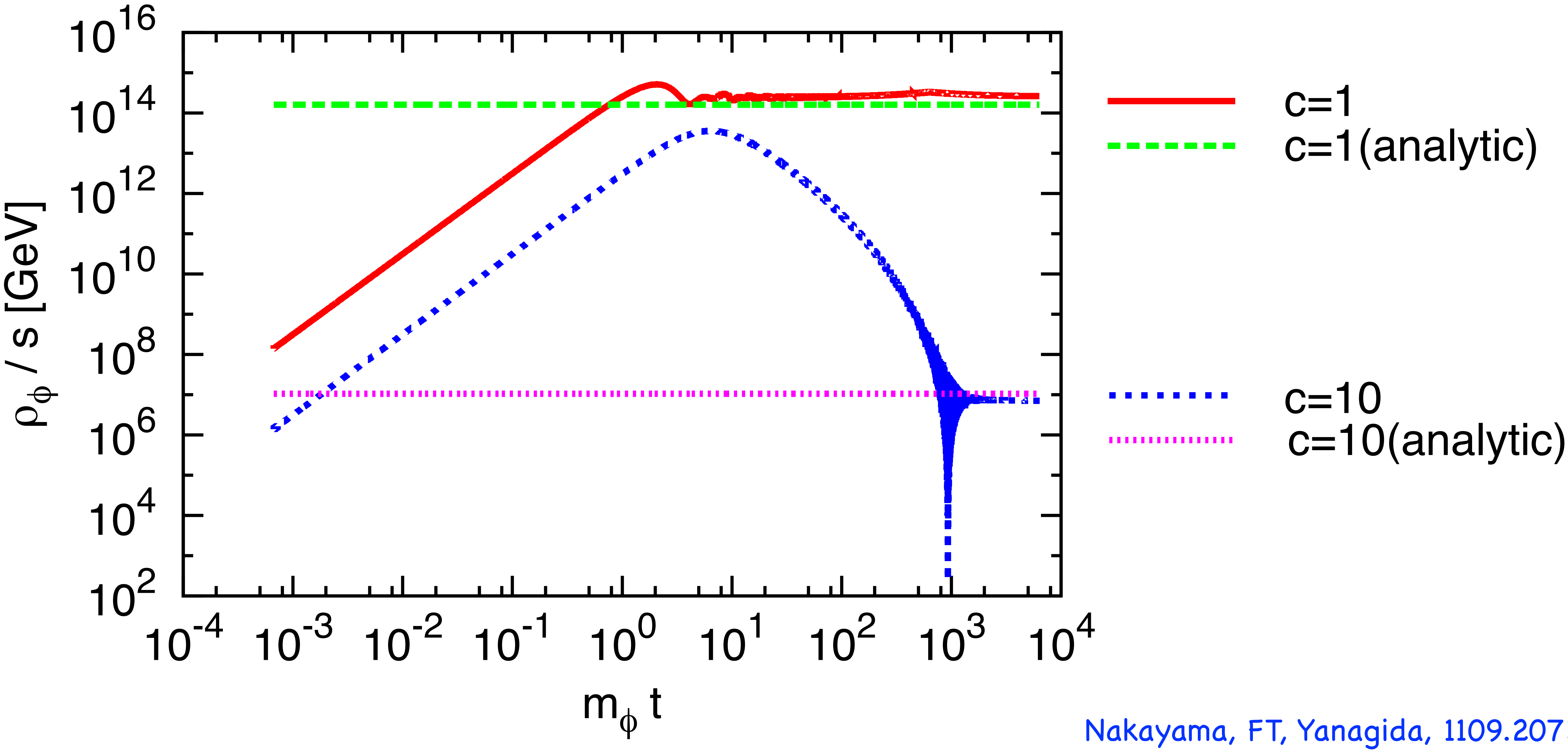
if one starts from t=0.

Linde (`96)

The moduli abundance is suppressed by S^2.

``Adiabatic suppression mechanism".

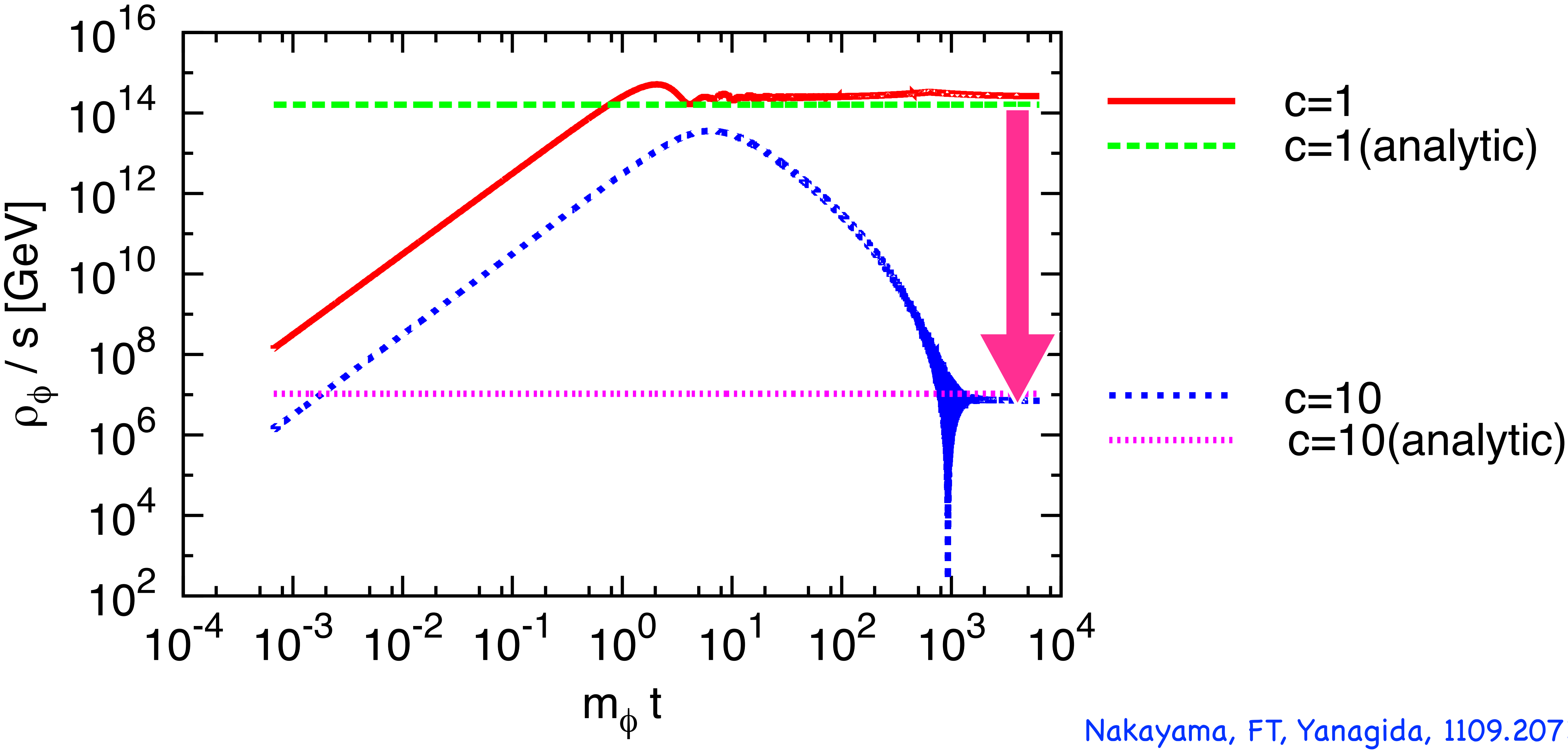
Numerical result



Nakayama, FT, Yanagida, 1109.2073

The moduli abundance is reduced significantly just by increasing c by a factor 10.

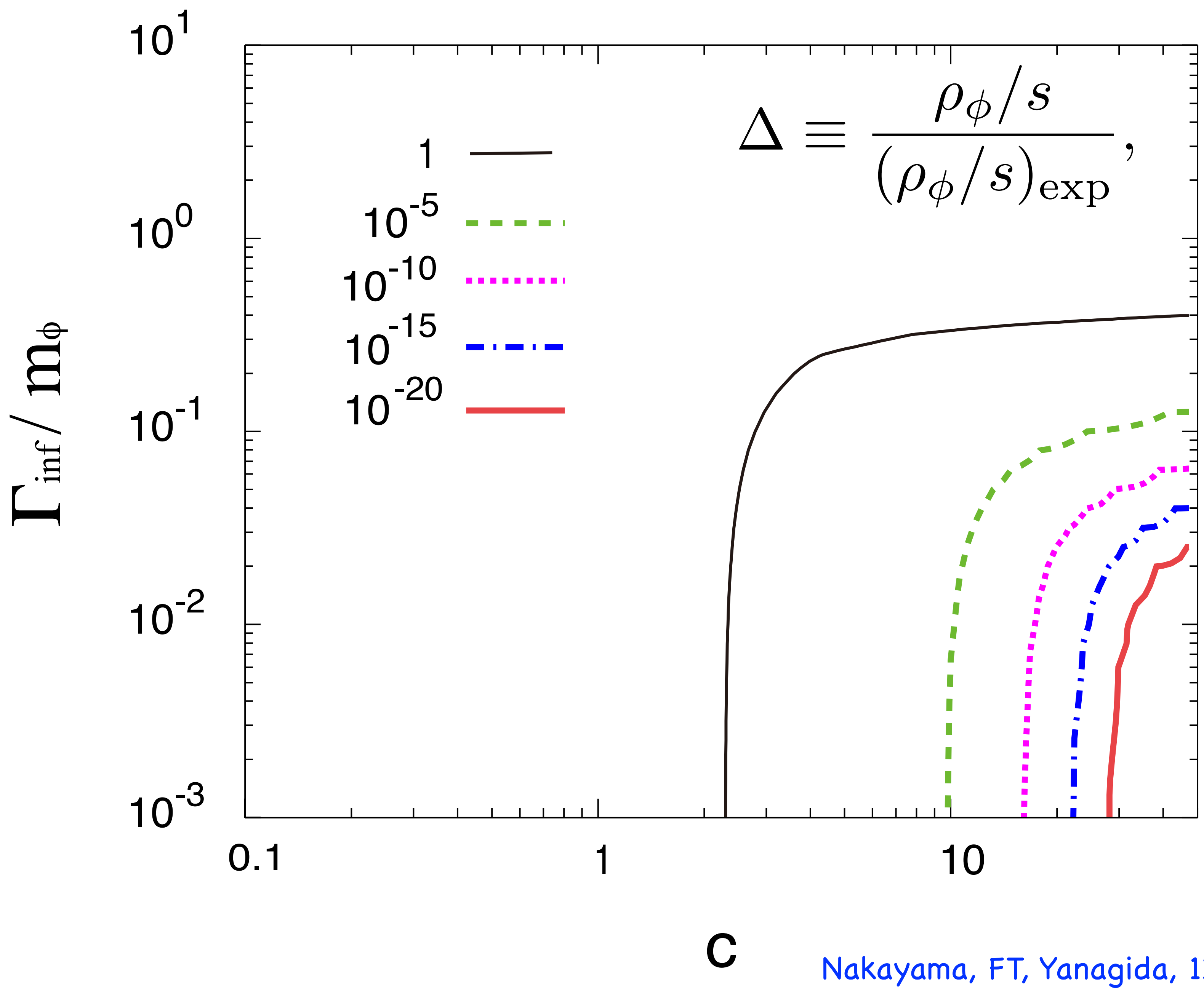
Numerical result



Nakayama, FT, Yanagida, 1109.2073

The moduli abundance is reduced significantly just by increasing c by a factor 10.

Contours of the suppression factor



Nakayama, FT, Yanagida, 1109.2073

Suppression of order 10^{-20} is possible if c > 30.

Reheating should take place after the modulus oscillation.

FT, Yanagida 1101.0867

Caveats

- Viable only when the potentials can be approximated by the quadratic form. Lukas, Niemeyer, Yamaguchi, `96
- The mechanism does not say anything about the initial abundance which is determined during the first period of oscillation. Nakayama, FT, Yanagida, 1109.2073
  - The inflaton dynamics in general makes additional contributions because $m_I \gg m_\phi$.

There are additional contributions which are not exponentially suppressed.

Additional contributions

Nakayama, FT, Yanagida, 1109.2073

- $H_{inf} < \infty$

$$\frac{\rho_\phi^{(i)}}{s} \sim \frac{9}{8} T_{\rm R} \left(\frac{\phi_*}{M_P}\right)^2 \left(\frac{m_\phi}{cH_i}\right)^5 .$$

- Single-field inflation

$$\frac{\rho_\phi^{(i)}}{s} \sim \frac{9}{32} T_{\rm R} \left(\frac{\phi_*}{M_P}\right)^2 \left(\frac{m_\phi}{c^3 H_{\rm inf}}\right) .$$

- Multi-field inflation

$$\frac{\rho_\phi^{(i)}}{s} \sim \frac{1}{8} T_{\rm R} \left(\frac{\phi_1 - \phi_2}{M_P}\right)^2 \left(\frac{c_2^4 m_\phi}{c_1^3 H_{\rm inf}}\right) .$$

Additional contributions

Nakayama, FT, Yanagida, 1109.2073

- $H_{\rm inf} < \infty$

$$\frac{\rho_\phi^{(i)}}{s} \sim \frac{9}{8} T_{\rm R} \left(\frac{\phi_*}{M_P}\right)^2 \boxed{\left(\frac{m_\phi}{cH_i}\right)^5}.$$

- Single-field inflation

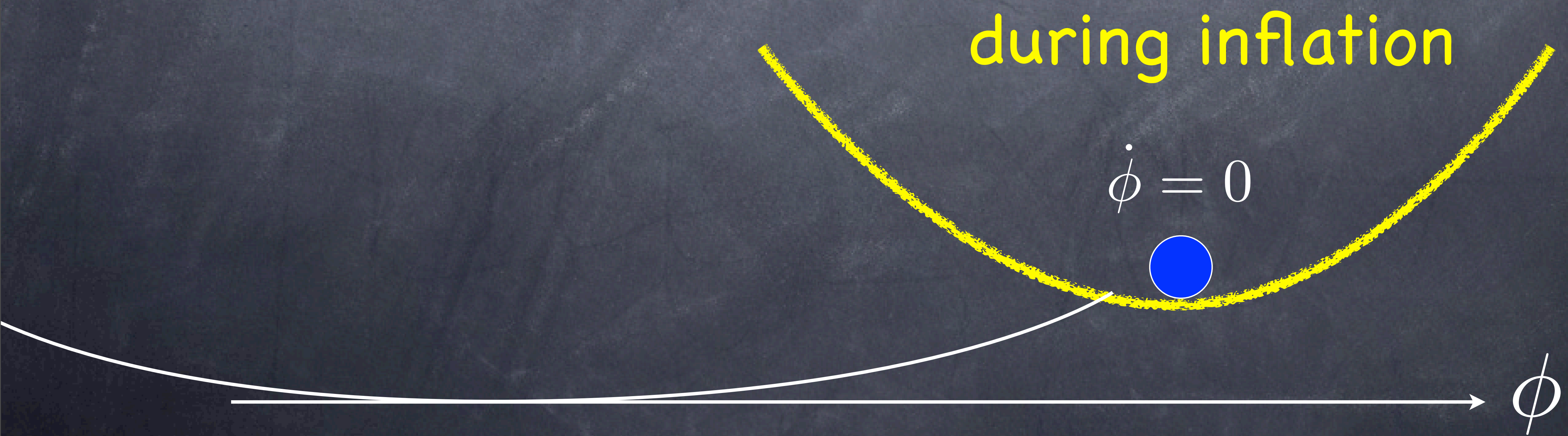
$$\frac{\rho_\phi^{(i)}}{s} \sim \frac{9}{32} T_{\rm R} \left(\frac{\phi_*}{M_P}\right)^2 \boxed{\left(\frac{m_\phi}{c^3 H_{\rm inf}}\right)}.$$

- Multi-field inflation

$$\frac{\rho_\phi^{(i)}}{s} \sim \frac{1}{8} T_{\rm R} \left(\frac{\phi_1 - \phi_2}{M_P}\right)^2 \boxed{\left(\frac{c_2^4 m_\phi}{c_1^3 H_{\rm inf}}\right)}.$$

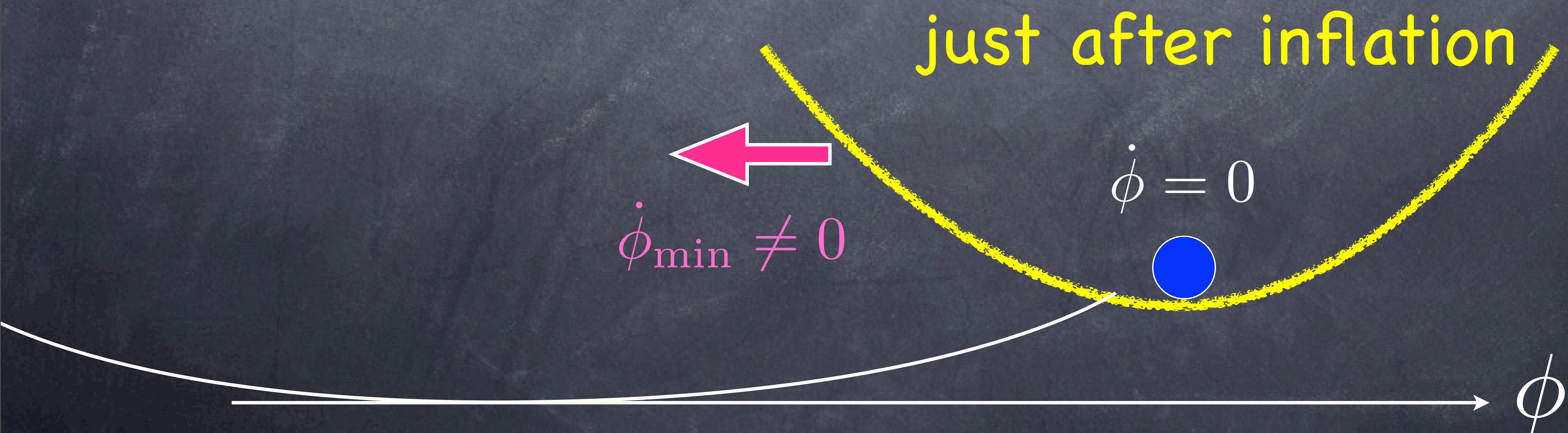
Finite inflation scale

- The moduli stays at the potential minimum during inflation.
- The Hubble-induced mass starts to change with time as $H \propto t^{-1}$, in a time scale of m_I^{-1}.
- The difference of the velocity results in the modulus production.



Finite inflation scale

- The moduli stays at the potential minimum during inflation.
- The Hubble-induced mass starts to change with time as $H \propto t^{-1}$, in a time scale of m_I^{-1}.
- The difference of the velocity results in the modulus production.



Single-field inflation

In general, the potential minimum moves at the end of inflation.

$$K = |\phi|^2 + |I|^2 + c^2 \frac{|\phi - \phi_*|^2 |I|^2}{M_P^2},$$

The relevant scalar potential reads

$$V = 3H_I^2 |\phi|^2 + c^2 H^2 |\phi - \phi_*|^2 \qquad c \gg 1$$

$$3H_I^2 M_P^2 \equiv V_{\rm inf}(I)$$

$$3H^2 M_P^2 = |\dot{I}|^2 + V_{\rm inf}(I)$$

Single-field inflation

In general, the potential minimum moves at the end of inflation.

$$K = |\phi|^2 + |I|^2 + c^2 \frac{|\phi - \phi_*|^2 |I|^2}{M_P^2},$$

The relevant scalar potential reads

$$V = 3H_I^2 |\phi|^2 + c^2 H^2 |\phi - \phi_*|^2 \qquad c \gg 1$$

Oscillates after inflation.

$$3H_I^2 M_P^2 \equiv V_{\rm inf}(I)$$

$$3H^2 M_P^2 = |\dot{I}|^2 + V_{\rm inf}(I)$$

$$\mathcal{L} = |\partial I|^2 - e^K (D_i W K^{i\bar{j}} D_{\bar{j}} W^\dagger - 3|W|^2)$$

Single-field inflation

In general, the potential minimum moves at the end of inflation.

$$K = |\phi|^2 + |I|^2 + c^2 \frac{|\phi - \phi_*|^2 |I|^2}{M_P^2},$$

The relevant scalar potential reads

$$V = 3H_I^2|\phi|^2 + c^2 H^2 |\phi - \phi_*|^2 \qquad c \gg 1$$

Oscillates after inflation.

$$3H_I^2 M_P^2 \equiv V_{\rm inf}(I)$$

$$3H^2 M_P^2 = |\dot{I}|^2 + V_{\rm inf}(I)$$

$$\mathcal{L} = |\partial I|^2 - e^K (D_i W K^{i\bar{j}} D_{\bar{j}} W^\dagger - 3|W|^2)$$

The moduli starts to oscillate with an amplitude $\sim \phi_*/c^2$

Multi-field inflation

e.g. hybrid inflation:

$$W = S(\mu^2 - \psi\bar{\psi})$$

During inflation, S has non-zero F-term.
After inflation both S and the waterfall fields oscillate.

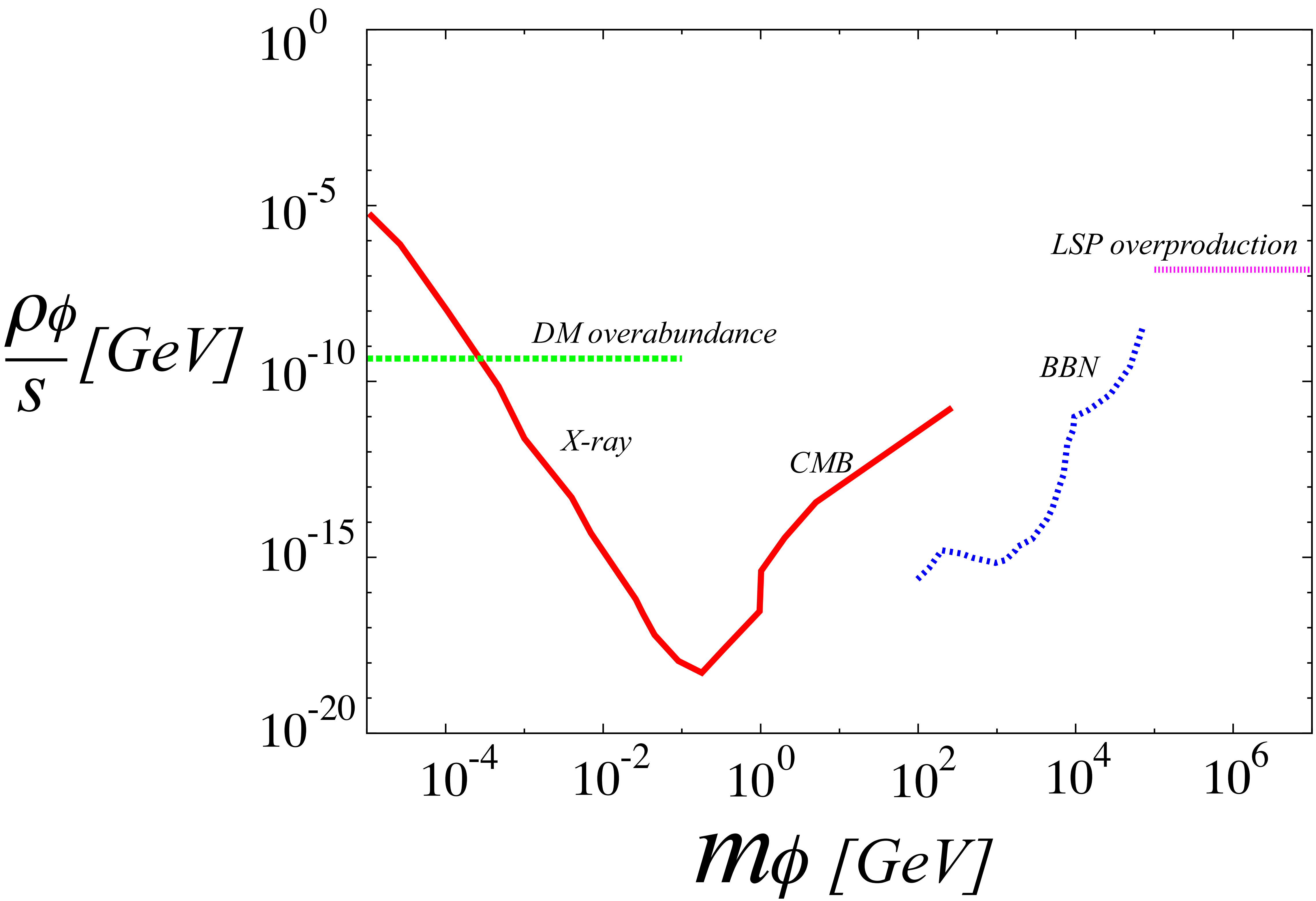
In general, the inflaton and the waterfall fields are coupled to the moduli in a different way.

$$K = \tilde{c}_1^2 \frac{|I_1|^2 |\phi - \phi_1|^2}{M_P^2} + \tilde{c}_2 \frac{|I_2|^2 |\phi - \phi_2|^2}{M_P^2},$$

The potential minimum changes at the end of inflation and the modulus oscillations are induced.

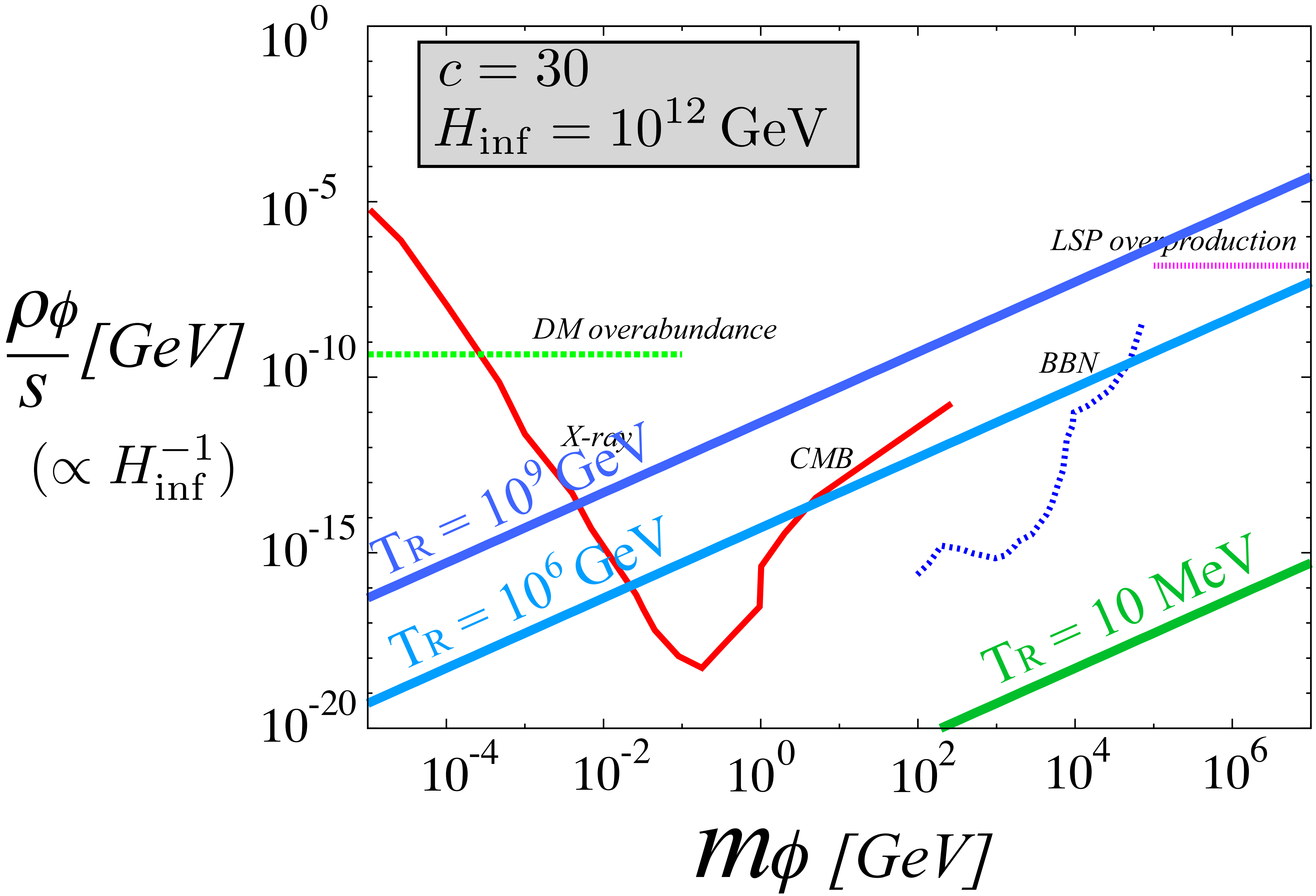
Cosmological constraints

$$\mathcal{L} = \frac{\phi}{4M_p} F_{\mu\nu} F^{\mu\nu}$$ is assumed



Cosmological constraints

$$\mathcal{L} = \frac{\phi}{4M_p} F_{\mu\nu} F^{\mu\nu}$$ is assumed



Summary of adiabatic suppression mechanism

- A large Hubble-induced mass is required.
- Viable only if the potential can be approximated by the quadratic term.
- The moduli abundance can be suppressed by a factor of $c^{-3}\frac{m_\phi}{H_{\rm inf}}$, but not exponentially suppressed in contrast to the original claim.

Modulus decay

Endo, Hamaguchi and F.T., hep-ph/0602061, hep-ph/0605091
Nakamura, Yamaguchi, hep-ph/0602081

If the modulus mass is heavier than 100TeV, it decays before BBN.

Then, is there no cosmological problem if such heavy moduli dominates the Universe?

If the modulus mass is heavier than 100TeV, it decays before BBN.

Then, is there no cosmological problem if such heavy moduli dominates the Universe?

1. Moduli-induced gravitino/LSP problem
2. Baryogenesis

Gravitino Pair-Production from scalar decay

Endo, Hamaguchi and F.T., hep-ph/0602061, Nakamura and Yamaguchi, hep-ph/0602081, Kawasaki, F.T. and Yanagida, hep-ph/0603265, 0605297, Asaka, Nakamura and Yamaguchi, hep-ph/0604132

- Relevant interactions:

$$
\begin{aligned}
e^{-1}\mathcal{L} \quad = \quad & -\frac{1}{8}\epsilon^{\mu\nu\rho\sigma}\left(G_\phi \partial_\rho \hat{\phi} + G_z \partial_\rho z - \mathrm{h.c.}\right)\bar{\psi}_\mu \gamma_\nu \psi_\sigma \\
& -\frac{1}{8}e^{G/2}\left(G_\phi \hat{\phi} + G_z z + \mathrm{h.c.}\right)\bar{\psi}_\mu \left[\gamma^\mu, \gamma^\nu\right]\psi_\nu,
\end{aligned}
$$

ϕ : any heavy scalar, e.g. moduli/inflaton

z : SUSY breaking field, w/ $G^z G_z \simeq 3$ $\qquad G \equiv K + \ln|W|^2$

Taking account of the mixings,

$$
G_\phi \sim \langle \phi \rangle \frac{m_{3/2}}{m_\phi} \quad \text{for} \quad m_\phi < m_z
$$

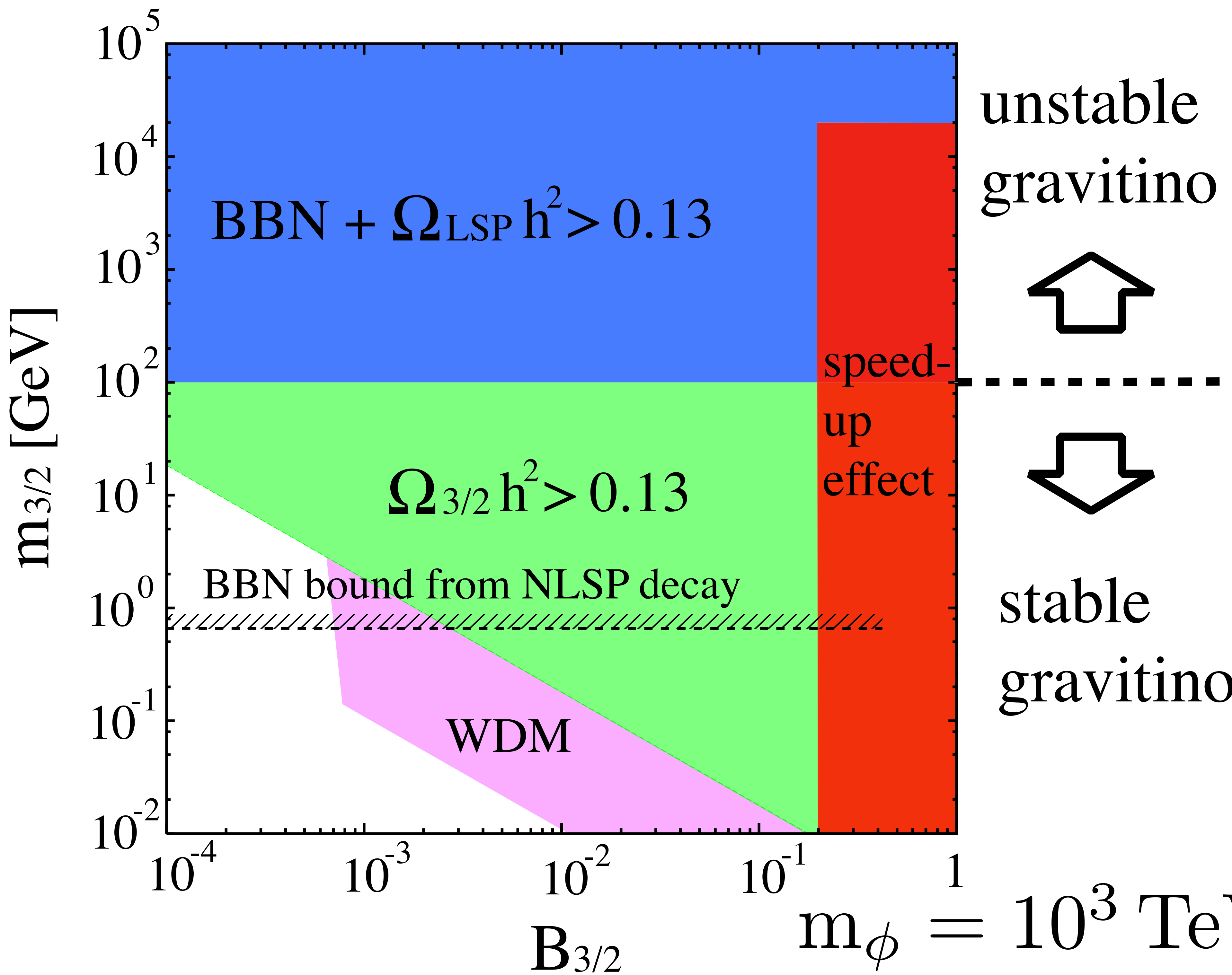
Gravitino Pair Production Rate:

$$\boxed{\Gamma_{3/2} \simeq \frac{|G_\phi|^2}{288\pi} \frac{m_\phi^5}{m_{3/2}^2 M_P^2} \simeq \frac{1}{32\pi} \left(\frac{\langle \phi \rangle}{M_P} \right)^2 \frac{m_\phi^3}{M_P^2}}$$

Endo, Hamaguchi and F.T., hep-ph/0602061
Nakamura and Yamaguchi, hep-ph/0602081

for $m_\phi < m_z$

- The branching fraction of the modulus decay into gravitinos can be sizable, if its coupling to the visible sector is Planck suppressed, and if it is kinematically allowed.



$$m_\phi = 10^3\ \mathrm{TeV}$$

$$B_{3/2} = 0.01 - 0.1$$

Endo, Hamaguchi and F.T., hep-ph/0602061

Solutions:

(i) Late-time entropy production;

Endo, Hamaguchi and F.T., hep-ph/0602061

K. Choi, K.S. Jeong, W.-I. Park and C.S. Shin, arXiv:0908.2154

(ii) Increasing the gravitino mass;

Nakamura and Yamaguchi, hep-ph/0602081

Naturalness? Low-energy SUSY?

(iii) R-parity violation;

DM candidate? Maybe axion?

(iv) Axino LSP? Nakamura, Okumura and Yamaguchi, arXiv:0803.3725

(v) Stronger coupling with the visible sector and suppressed coupling with gravitinos in LVS

Conlon, Quevedo, 0705.3460

Baryogenesis, Moduli problem and LVS

Kamada, Higaki, FT, 1207.2771

- Some of the moduli, especially heavy ones, may not be produced if the inflation scale is low.
- Still the lightest one may lead to the cosmological moduli problem.
- Even if it decays before BBN, we need an efficient baryogenesis.
- Also the moduli-induced gravitino problem should be avoided.

→ We consider Affleck-Dine mechanism and Large Volume scenario.

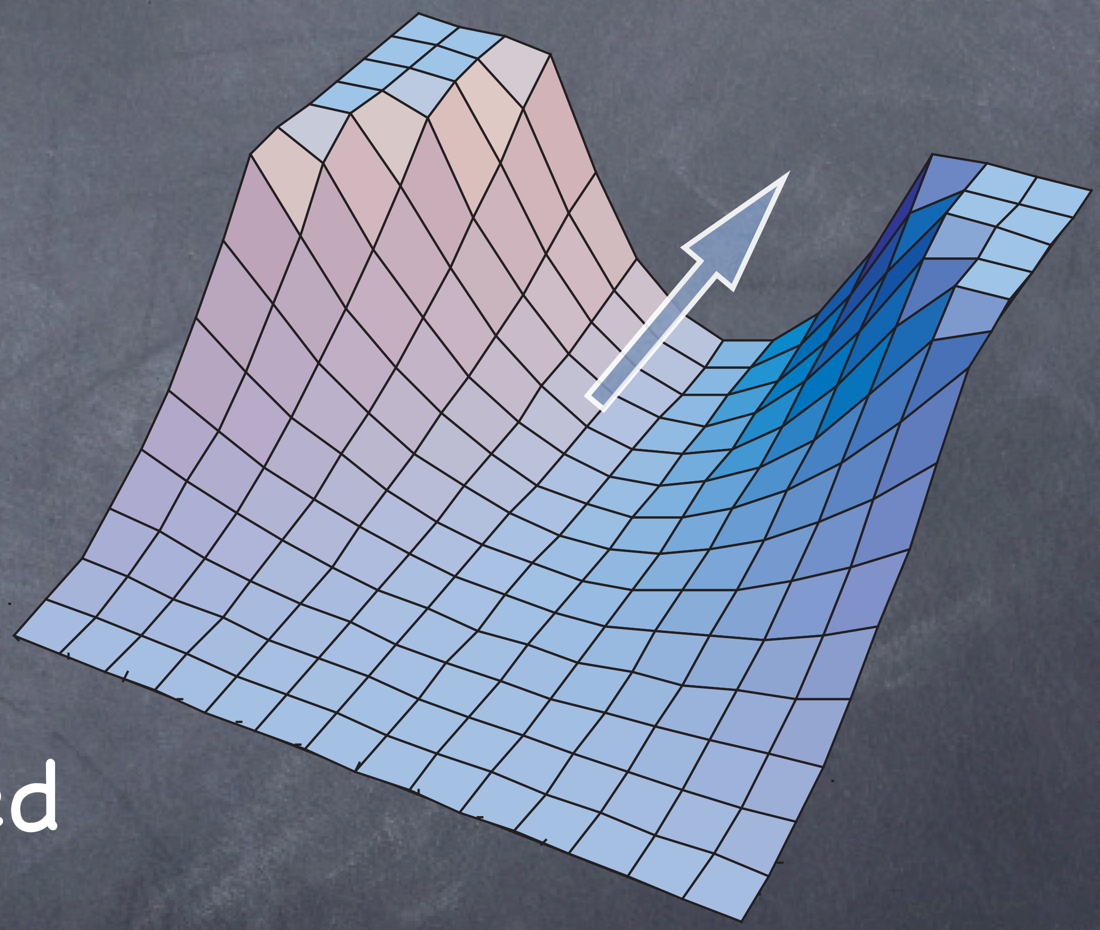
Balasubramanian, Berglund, Conlon and Quevedo, hep-th/0502058
Conlon, Quevedo, Suruliz, hep-th/0505076
Blumenhagen, Msoster, Plaushim, 0806.2667
Cicoli, Conlon, Quevedo, 0805.1029

Affleck-Dine mechanism

Affleck, Dine (1985)

In the SUSY SM, there are many flat directions composed of squarks and/or sleptons.

(e.g. udd, eLL)



A flat direction is parametrized by a complex scalar field Φ (AD field). e.g. $\mathrm{udd} = \Phi^3$

Scalar potential of the AD field

Flat directions are lifted by SUSY breaking and non-renormalizable operators.

$$W_{\rm NR} = \frac{\Phi^n}{M_*^{n-3}} \qquad (n = 4-9)$$

e.g.) $W = (LH_u)^2, (udd)^2, (eLL)^2$

U(1)-preserving terms U(1)-breaking terms

$$V(\Phi) = \left(m_0^2 - c^2 H^2\right)|\Phi|^2 + \frac{n^2|\Phi|^{2n-2}}{M_*^{2n-6}} + \left(A_n \frac{\Phi^n}{M_*^{n-3}} + {\rm h.c.}\right)$$

Scalar potential of the AD field

Flat directions are lifted by SUSY breaking and non-renormalizable operators.

$$W_{\rm NR} = \frac{\Phi^n}{M_*^{n-3}} \qquad (n = 4-9)$$

e.g.) $W = (LH_u)^2,\ (udd)^2,\ (eLL)^2$

U(1)-preserving terms

U(1)-breaking terms

$$V(\Phi) = \left(m_0^2 - c^2 H^2\right)|\Phi|^2 + \frac{n^2|\Phi|^{2n-2}}{M_*^{2n-6}} + \left(A_n \frac{\Phi^n}{M_*^{n-3}} + {\rm h.c.}\right)$$

soft mass

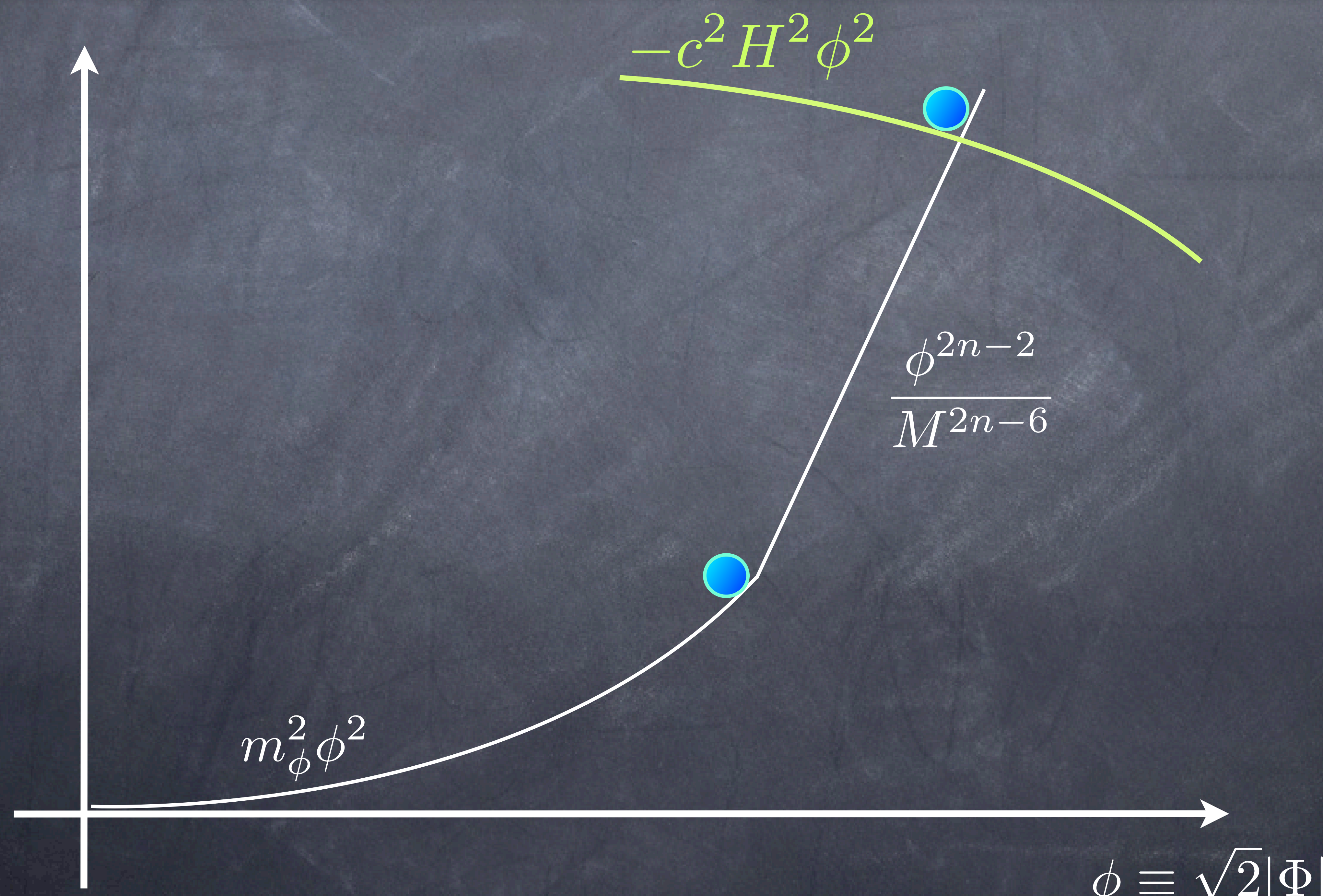
due to inflaton

non-ren. operator

A-term: NR operator and ~~U(1)~~R

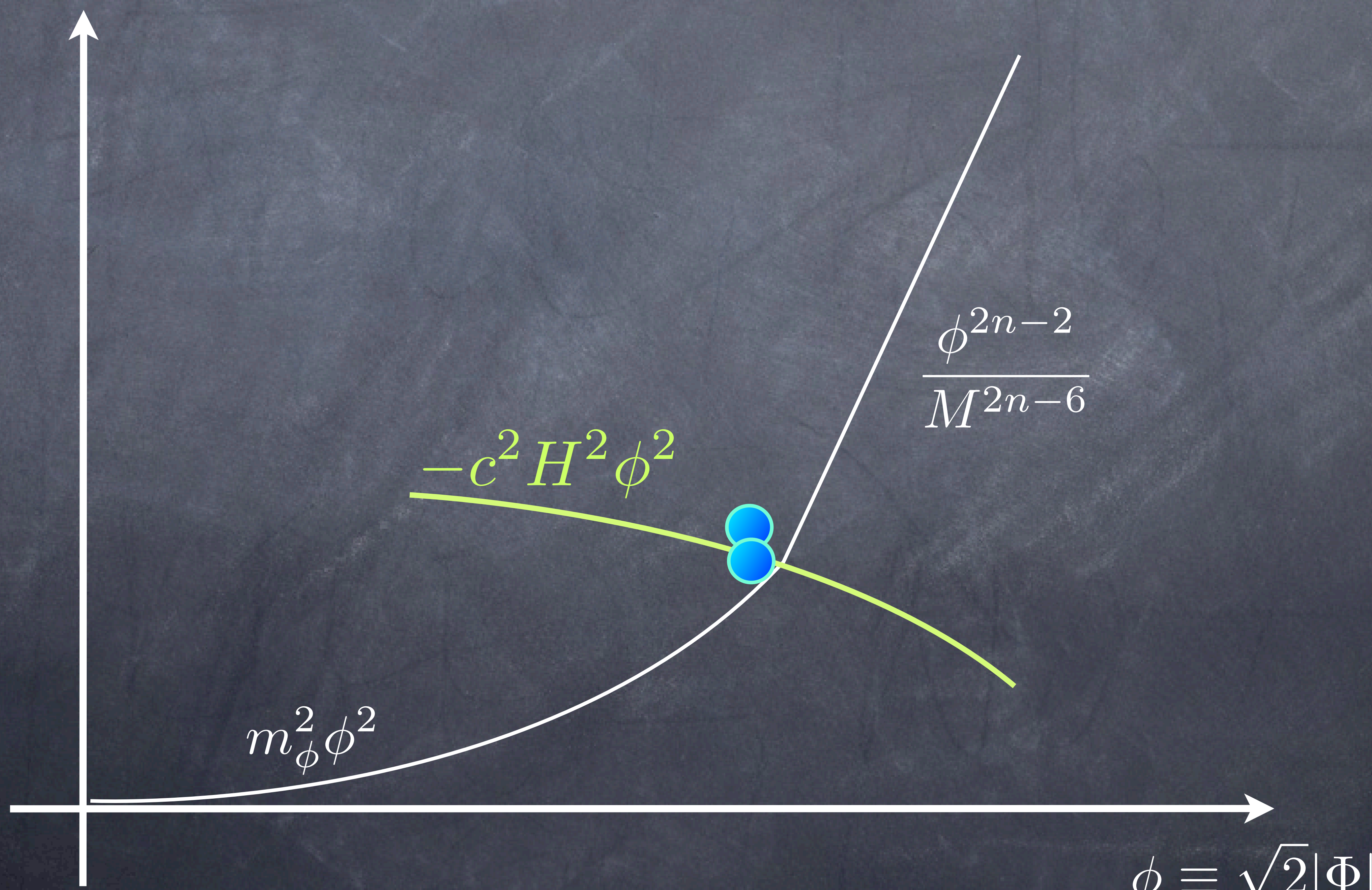
Dynamics of the AD field

1. Takes a large VEV during inflation
2. Follows the instantaneous min. after inflation.
3. Starts to oscillate and kicked into the phase direction.



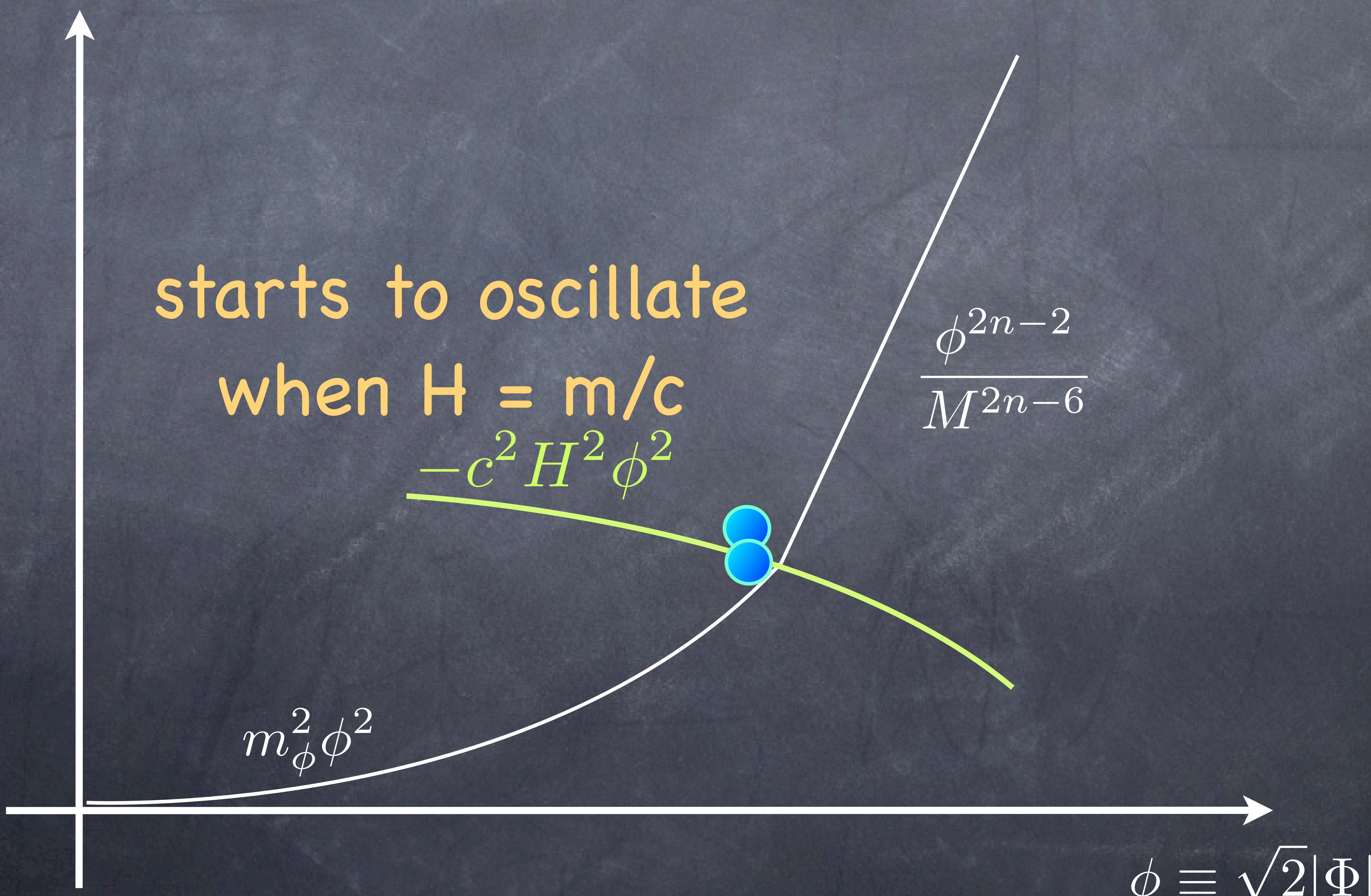
Dynamics of the AD field

1. Takes a large VEV during inflation
2. Follows the instantaneous min. after inflation.
3. Starts to oscillate and kicked into the phase direction.



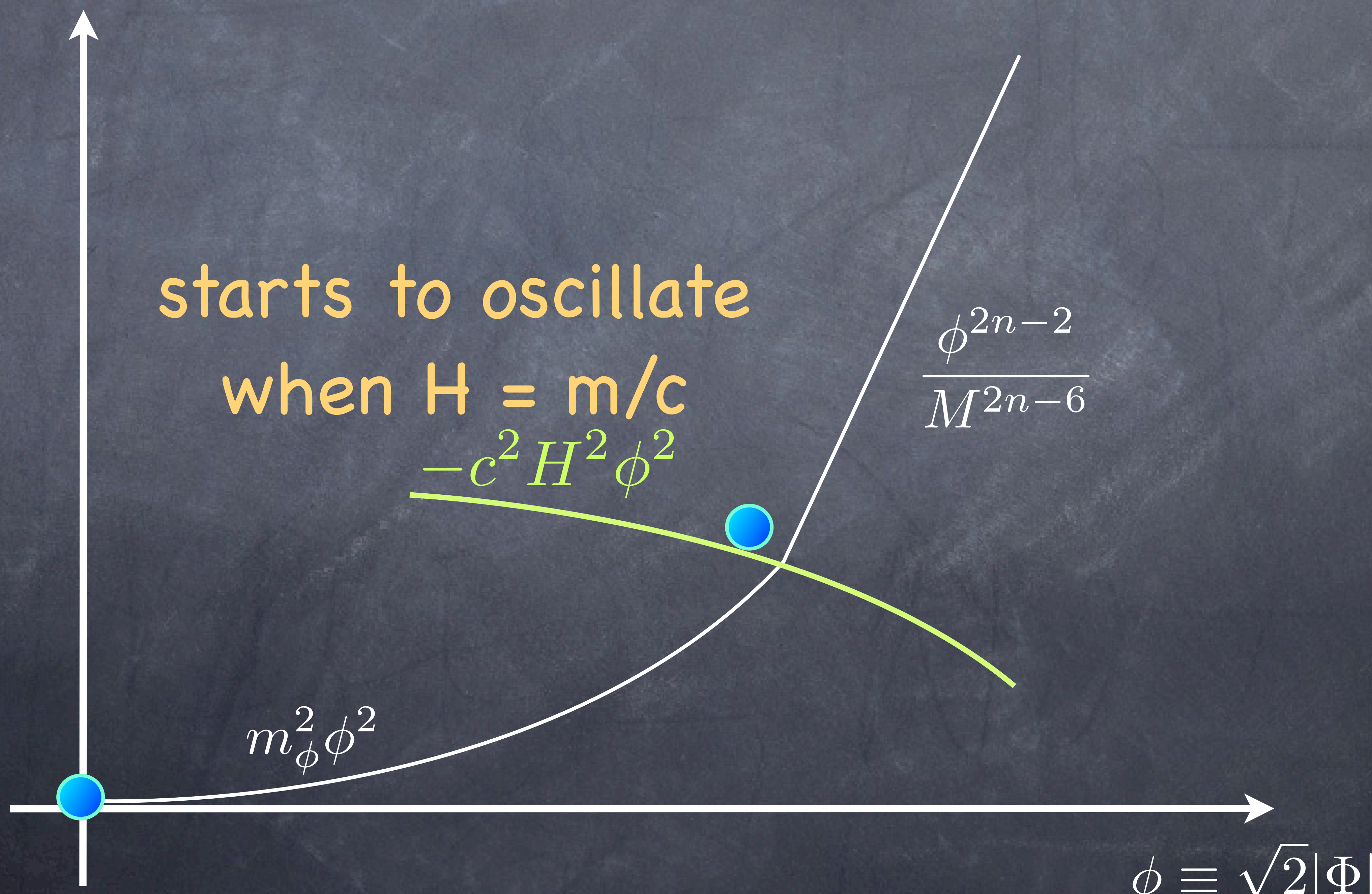
Dynamics of the AD field

1. Takes a large VEV during inflation
2. Follows the instantaneous min. after inflation.
3. Starts to oscillate and kicked into the phase direction.



Dynamics of the AD field

1. Takes a large VEV during inflation
2. Follows the instantaneous min. after inflation.
3. Starts to oscillate and kicked into the phase direction.



The negative Hubble-induced mass is required:

$$K = \frac{|\Phi|^2 |I|^2}{M^2}$$

If a massive mode is coupled to both, the cut-off scale is given by its mass.

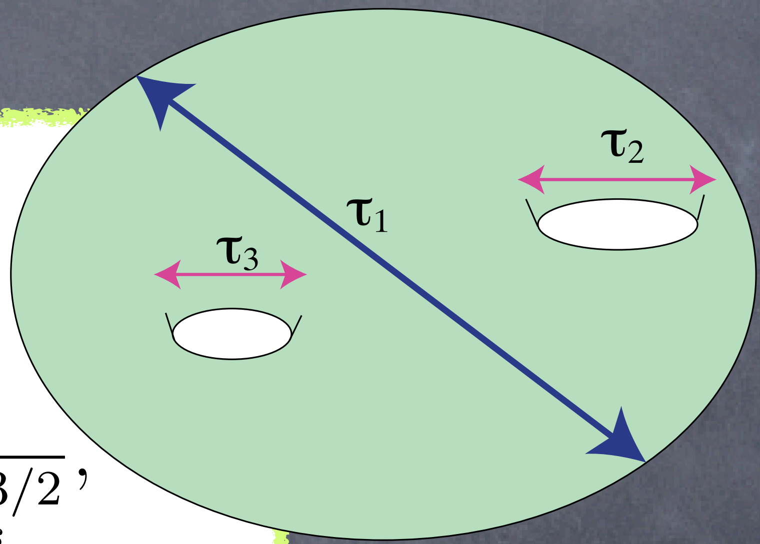
$$M_{KK} \sim \frac{1}{R} \sim \frac{M_{\rm pl}}{\mathcal{V}^{2/3}}, \quad M_{\rm string} \sim \frac{M_{\rm pl}}{\mathcal{V}^{1/2}}, \quad M_{\rm wind} \sim M_{\rm string}^2 R \sim \frac{M_{\rm pl}}{\mathcal{V}^{1/3}}$$

$$c \sim \mathcal{V}^{2/3}, \quad \mathcal{V}^{1/2} \quad \text{or} \quad \mathcal{V}^{1/3}, \quad >> 1$$

The baryon asymmetry is enhanced by c or c^3.
The AD mechanism may work even in the low-scale inflation.

We assume the type IIB orientifold flux compactifications, and consider an extended version of Large Volume Scenario with poly-instanton corrections.

Blumenhagen, Moster, Plauschinn, 0806.2667



$$K = -2\log\left(\mathcal{V} + \frac{\xi}{2}\right),$$

$$\mathcal{V} = (\eta_1\tau_1)^{3/2} - (\eta_2\tau_2)^{3/2} - (\eta_3\tau_3)^{3/2}, \qquad \xi = -\frac{\chi\zeta(3)}{2(2\pi)^3 g_s^{3/2}},$$

$$\begin{aligned} W &= Ae^{-a(T_2+C_1e^{-2\pi T_3})} - Be^{-b(T_2+C_2e^{-2\pi T_3})}, \\ &= Ae^{-aT_2} - Be^{-bT_2} - (aAC_1e^{-aT_2} - bBC_2e^{-bT_2})e^{-2\pi T_3} + \cdots, \\ &\equiv W_{\text{eff}} + A_{\text{eff}}e^{-2\pi T_3} + \cdots. \end{aligned}$$

$$T_i = \tau_i + i\sigma_i. \qquad \chi < 0$$

$$\eta_{i=1,2,3} = \mathcal{O}(0.1-1), \quad g_s = \mathcal{O}(0.1), \quad C_{i=1,2},\ a,b = \mathcal{O}(1), \quad \chi = -\mathcal{O}(100) < 0,$$

$$A, B \gg 1.$$

2012年8月7日火曜日

A numerical example:

$$\eta_1 = 1, \quad \eta_2 = \frac{1}{53}, \quad \eta_3 = \frac{1}{6}, \quad \chi = -136, \quad g_s = \frac{2}{5},$$

$$C_1 = 1, \quad C_2 = 3, \quad a = \frac{2\pi}{8}, \quad b = \frac{2\pi}{9},$$

$$A = 1.28 \times 10^5, \quad B = 1.6 \times 10^4.$$

$$\Rightarrow \quad \langle \mathcal{V} \rangle = 78559, \qquad \langle T_2 \rangle = 25.18, \qquad \langle T_3 \rangle = 2.88.$$

We assume that the MSSM sector is localized on the D7 brane wrapping on the τ_2 4-cycle.

Mass spectra

$$K_{\rm vis} = \frac{(T_2+T_2^\dagger)^{\lambda_i}}{(T_1+T_1^\dagger)}|\phi_i|^2 = Z_i|\phi_i|^2, \qquad f_{{\rm vis},a} = \frac{1}{4\pi}(T_2+h_aS), \qquad W_{\rm vis} = W_{\rm MSSM}(\phi_{\rm vis}).$$

$$\begin{aligned}
m_0^2 &\simeq -F^I(F^{\bar J})^\dagger \partial_I\partial_{\bar J}\log(e^{-K_{\rm moduli}/3}Z) \\
&\sim \frac{1}{\mathcal{V}}\left|\frac{F^{T_1}}{2\tau_1}\right|^2 \simeq \frac{m_{3/2}^2}{\mathcal{V}} \sim \frac{\langle|W_{\rm eff}|^2\rangle}{\mathcal{V}^3}, \\
M_a &\simeq F^I\partial_I\log(f_{{\rm vis},a}) + \frac{\alpha_a}{4\pi}\left(b_aF^\varphi - 2\sum_i {\rm tr}(T_a^2(\phi_i))F^I\partial_I\log(e^{-K_{\rm moduli}/3}Z_i)\right) \\
&\simeq h_a\frac{F^S}{2\tau_2} + \frac{\alpha_a}{4\pi}\frac{1}{\mathcal{V}}\frac{F^{T_1}}{2\tau_1} \sim \frac{m_{3/2}}{\log(\mathcal{V})\mathcal{V}} \sim \frac{\langle W_{\rm eff}\rangle}{\log(\mathcal{V})\mathcal{V}^2}, \\
A_{i_1\cdots i_n} &\simeq (n-3)F^\varphi - F^I\partial_I\log\left(\frac{y_{i_1\cdots i_n}}{e^{-nK_{\rm moduli}/3}Z_{i_1}\cdots Z_{i_n}}\right) \\
&\sim \frac{1}{\mathcal{V}}\frac{F^{T_1}}{2\tau_1} + \frac{F^S}{S+S^\dagger} \sim \frac{m_{3/2}}{\mathcal{V}} \sim \frac{\langle W_{\rm eff}\rangle}{\mathcal{V}^2}.
\end{aligned}$$

Mass spectra

$$K_{\rm vis} = \frac{(T_2+T_2^\dagger)^{\lambda_i}}{(T_1+T_1^\dagger)}|\phi_i|^2 = Z_i|\phi_i|^2, \qquad f_{{\rm vis},a} = \frac{1}{4\pi}(T_2+h_a S), \qquad W_{\rm vis} = W_{\rm MSSM}(\phi_{\rm vis}).$$

$$m_{\tau_2} > m_{S,U} \gg m_{\tau_3} > m_{3/2} > m_0 \gtrsim m_{\tau_1} \gg A_n > M_a.$$

Fundamental parameters	Moduli masses	F-terms	Soft masses
$M_{\rm string} = 1.2\times 10^{16}$ GeV	$m_{S,U} = 3.4\times 10^{13}$ GeV	$F^S = \mathcal{O}(10^3)$ GeV	$m_{3/2} = 1.4\times 10^9$ GeV
$M_* = 7.9\times 10^{16}$ GeV	$m_{\tau_2,\sigma_2} = 3.1\times 10^{17}$ GeV	$F^{T_2}/2\tau_2 = \mathcal{O}(10)$ GeV	$m_0 = \mathcal{O}(10^6-10^7)$ GeV
$\lvert W_{\rm eff}\rvert/M_{\rm pl}^3 = 4.1\times 10^{-5}$	$m_{\tau_3,\sigma_3} = 5.3\times 10^{10}$ GeV	$F^{T_3}/2\tau_3 = 2.9\times 10^7$ GeV	$A_n = \mathcal{O}(10^3-10^4)$ GeV
$\langle\mathcal{V}\rangle = 78559$	$m_{\tau_1} = 1.5\times 10^6$ GeV	$F^{T_1}/2\tau_1 = 1.4\times 10^9$ GeV	$M_{1/2} = \mathcal{O}(10^3)$ GeV

Mass spectra

$$K_{\text{vis}} = \frac{(T_2 + T_2^\dagger)^{\lambda_i}}{(T_1 + T_1^\dagger)} |\phi_i|^2 = Z_i |\phi_i|^2, \qquad f_{\text{vis},a} = \frac{1}{4\pi}(T_2 + h_a S), \qquad W_{\text{vis}} = W_{\text{MSSM}}(\phi_{\text{vis}}).$$

$$m_{\tau_2} > m_{S,U} \gg m_{\tau_3} > m_{3/2} > m_0 \gtrsim m_{\tau_1} \gg A_n > M_a.$$

Fundamental parameters	Moduli masses	F-terms	Soft masses
$M_{\text{string}} = 1.2 \times 10^{16}$ GeV	$m_{S,U} = 3.4 \times 10^{13}$ GeV	$F^S = \mathcal{O}(10^3)$ GeV	$m_{3/2} = 1.4 \times 10^9$ GeV
$M_* = 7.9 \times 10^{16}$ GeV	$m_{\tau_2,\sigma_2} = 3.1 \times 10^{17}$ GeV	$F^{T_2}/2\tau_2 = \mathcal{O}(10)$ GeV	$m_0 = \mathcal{O}(10^6 - 10^7)$ GeV
$\lvert W_{\text{eff}}\rvert / M_{\text{pl}}^3 = 4.1 \times 10^{-5}$	$m_{\tau_3,\sigma_3} = 5.3 \times 10^{10}$ GeV	$F^{T_3}/2\tau_3 = 2.9 \times 10^7$ GeV	$A_n = \mathcal{O}(10^3 - 10^4)$ GeV
$\langle \mathcal{V} \rangle = 78559$	$m_{\tau_1} = 1.5 \times 10^6$ GeV	$F^{T_1}/2\tau_1 = 1.4 \times 10^9$ GeV	$M_{1/2} = \mathcal{O}(10^3)$ GeV

Moduli decay

$$\begin{pmatrix} \delta\tau_1 \\ \delta\tau_2 \\ \delta\tau_3 \\ \delta(1/g_s) \end{pmatrix} \sim \begin{pmatrix} \mathcal{V}^{2/3} \\ \frac{m_{3/2}}{m_{\tau_2}} \\ \frac{m_{3/2}}{m_{\tau_3}} \\ \mathcal{V}^{-1/2} \end{pmatrix} \delta\phi_1 + \begin{pmatrix} \mathcal{V}^{1/6} \\ \mathcal{V}^{1/2} \\ \mathcal{V}^{-1/2} \\ \mathcal{V}^{-1} \end{pmatrix} \delta\phi_2 + \begin{pmatrix} \mathcal{V}^{1/6} \\ \mathcal{V}^{-1/2} \\ \mathcal{V}^{1/2} \\ \mathcal{V}^{-1} \end{pmatrix} \delta\phi_3 + \begin{pmatrix} \mathcal{V}^{1/6} \\ \mathcal{V}^{-1/2} \\ \mathcal{V}^{-1/2} \\ \mathcal{O}(1) \end{pmatrix} \delta\phi_s,$$

Through mixing with T_2, the lightest moduli is coupled to the gauginos as

$$\mathcal{L} = \delta\phi_1 \frac{m_{3/2}}{M_{\rm pl}} \lambda\lambda + \text{h.c.}$$

$$\Gamma_{\phi_1} \sim \frac{N_c}{4\pi} \left(\frac{m_{3/2}}{M_{\rm pl}}\right)^2 m_{\tau_1} \;\Rightarrow\; T_{\rm dec}^{\phi_1} \simeq 600\,{\rm GeV} \left(\frac{m_{\tau_1}}{10^6{\rm GeV}}\right)^{1/2} \left(\frac{m_{3/2}}{10^9{\rm GeV}}\right).$$

Moduli decay

$$\begin{pmatrix} \delta\tau_1 \\ \delta\tau_2 \\ \delta\tau_3 \\ \delta(1/g_s) \end{pmatrix} \sim \begin{pmatrix} \mathcal{V}^{2/3} \\ \boxed{\frac{m_{3/2}}{m_{\tau_2}}} \\ \frac{m_{3/2}}{m_{\tau_3}} \\ \mathcal{V}^{-1/2} \end{pmatrix} \delta\phi_1 + \begin{pmatrix} \mathcal{V}^{1/6} \\ \mathcal{V}^{1/2} \\ \mathcal{V}^{-1/2} \\ \mathcal{V}^{-1} \end{pmatrix} \delta\phi_2 + \begin{pmatrix} \mathcal{V}^{1/6} \\ \mathcal{V}^{-1/2} \\ \mathcal{V}^{1/2} \\ \mathcal{V}^{-1} \end{pmatrix} \delta\phi_3 + \begin{pmatrix} \mathcal{V}^{1/6} \\ \mathcal{V}^{-1/2} \\ \mathcal{V}^{-1/2} \\ \mathcal{O}(1) \end{pmatrix} \delta\phi_s,$$

Through mixing with T_2, the lightest moduli is coupled to the gauginos as

$$\mathcal{L} = \delta\phi_1 \frac{m_{3/2}}{M_{\rm pl}} \lambda\lambda + \text{h.c.}$$

$$\Gamma_{\phi_1} \sim \frac{N_c}{4\pi}\left(\frac{m_{3/2}}{M_{\rm pl}}\right)^2 m_{\tau_1} \quad \Rightarrow \quad T_{\rm dec}^{\phi_1} \simeq 600\,\text{GeV}\left(\frac{m_{\tau_1}}{10^6\,\text{GeV}}\right)^{1/2}\left(\frac{m_{3/2}}{10^9\,\text{GeV}}\right).$$

Baryon Asymmetry

$$\frac{n_B}{s}(t_0) \sim 10^{-10}\delta_{\rm eff}\left(\frac{c}{10}\right)\left(\frac{T_{\rm dec}^{\phi_1}}{10^3{\rm GeV}}\right)\left(\frac{m_0}{10^6{\rm GeV}}\right)^{-1}\left(\frac{\phi_{c,{\rm osc}}}{10^{14}{\rm GeV}}\right)^2 \times \left(\frac{\Delta\phi_1}{M_{\rm pl}}\right)^{-2}$$

The right amount of the baryon asymmetry can be created by the AD mechanism, in the presence of the entropy production by the modulus decay.

Moduli Curvaton

Kawasaki, Kobayashi, FT, 1107.6011

Curvaton

Linde, Mukhanov `97
Enqvist and Sloth `01
Lyth and Wands `01
Moroi and Takahashi `01

- Curvaton is an alternative mechanism for generating the density perturbation.
- Inflation model building becomes easier.
- Non-Gaussianity can be generated, which, if discovered, will exclude a simple inflation model.

Curvaton

Linde, Mukhanov `97
Enqvist and Sloth `01
Lyth and Wands `01
Moroi and Takahashi `01

1. Light during inflation

$$m \lesssim 0.1 H_{\rm inf}$$

The light mass can be naturally realized if the curvaton has an approximate shift symmetry.

2. Comes close to dominating the Universe

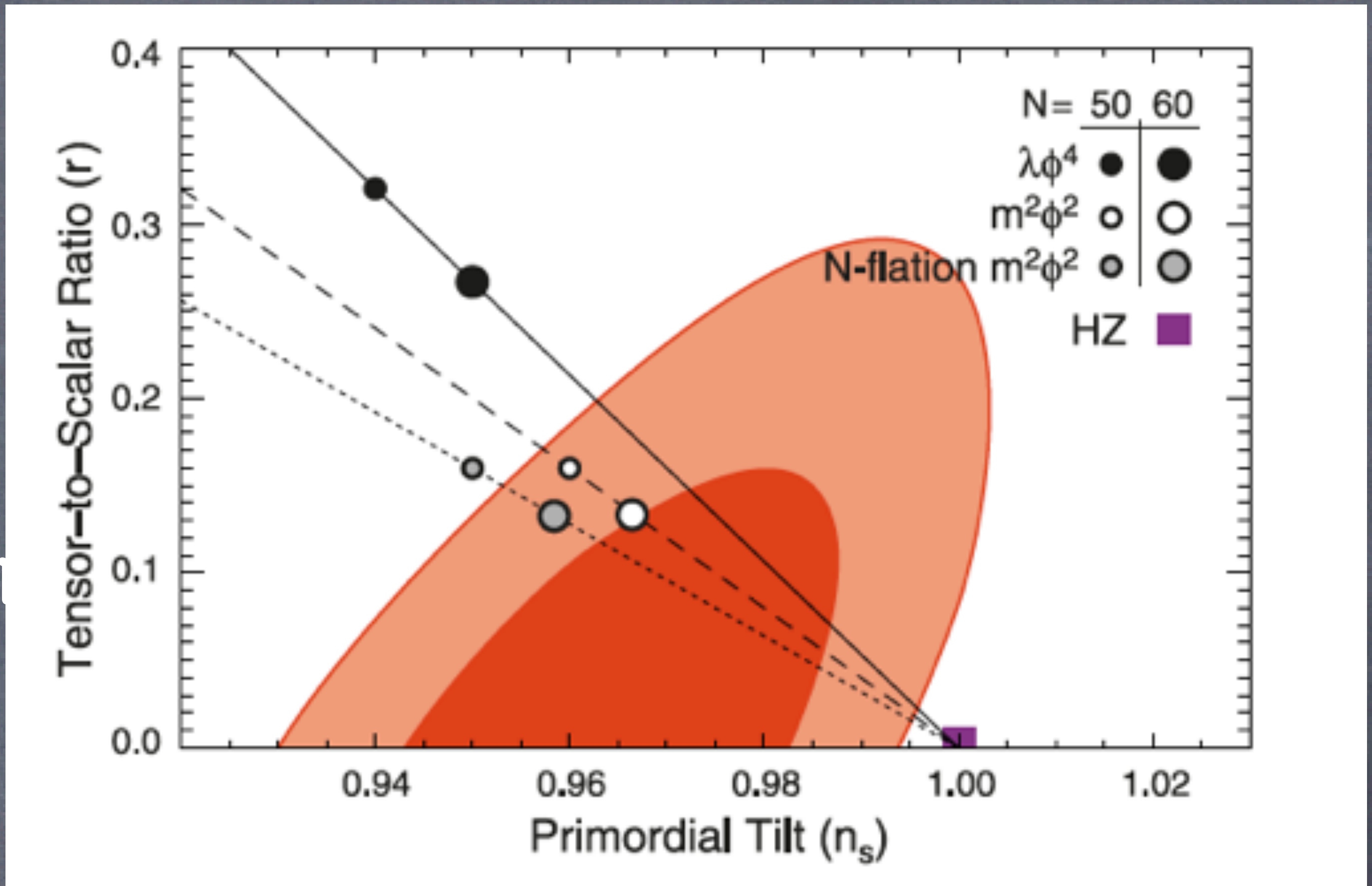
$$r \equiv \left. \frac{\rho_\sigma}{\rho_r} \right|_{\rm decay} > \mathcal{O}(0.01)$$

Lore of curvaton

- $f_{NL} \sim 1/r$ (?)
  - If we want to have $f_{NL} = O(10)$, isn't this a fine-tuning? Another puzzle?
- $n_s = 1$ (?)
  - Two-point functions should be consistent with obs. before talking about three-point function.

Lore of curvaton

- $f_{NL} \sim 1/r$ (?)
  - If we want to have fine-tuning? Anothe



- $n_s = 1$ (?)
  - Two-point functions should be consistent with obs. before talking about three-point function.

What does $\mathrm{n}_s < 1$ mean?

Formula: $$n_s - 1 \simeq \frac{2}{3}\frac{V''(\sigma_*)}{H_*^2} + 2\frac{\dot{H}_*}{H_*^2}$$

σ : curvaton

What does $n_s < 1$ mean?

Formula: $$n_s - 1 \simeq \boxed{\frac{2}{3}\frac{V''(\sigma_*)}{H_*^2}} + 2\frac{\dot{H}_*}{H_*^2}$$

σ : curvaton

What does $n_s < 1$ mean?

Formula: $$n_s - 1 \simeq \boxed{\frac{2}{3}\frac{V''(\sigma_*)}{H_*^2}} + \boxed{2\frac{\dot{H}_*}{H_*^2}}$$

σ : curvaton

What does $n_s < 1$ mean?

Formula: $$n_s - 1 \simeq \boxed{\frac{2}{3}\frac{V''(\sigma_*)}{H_*^2}} + \boxed{2\frac{\dot{H}_*}{H_*^2}}$$

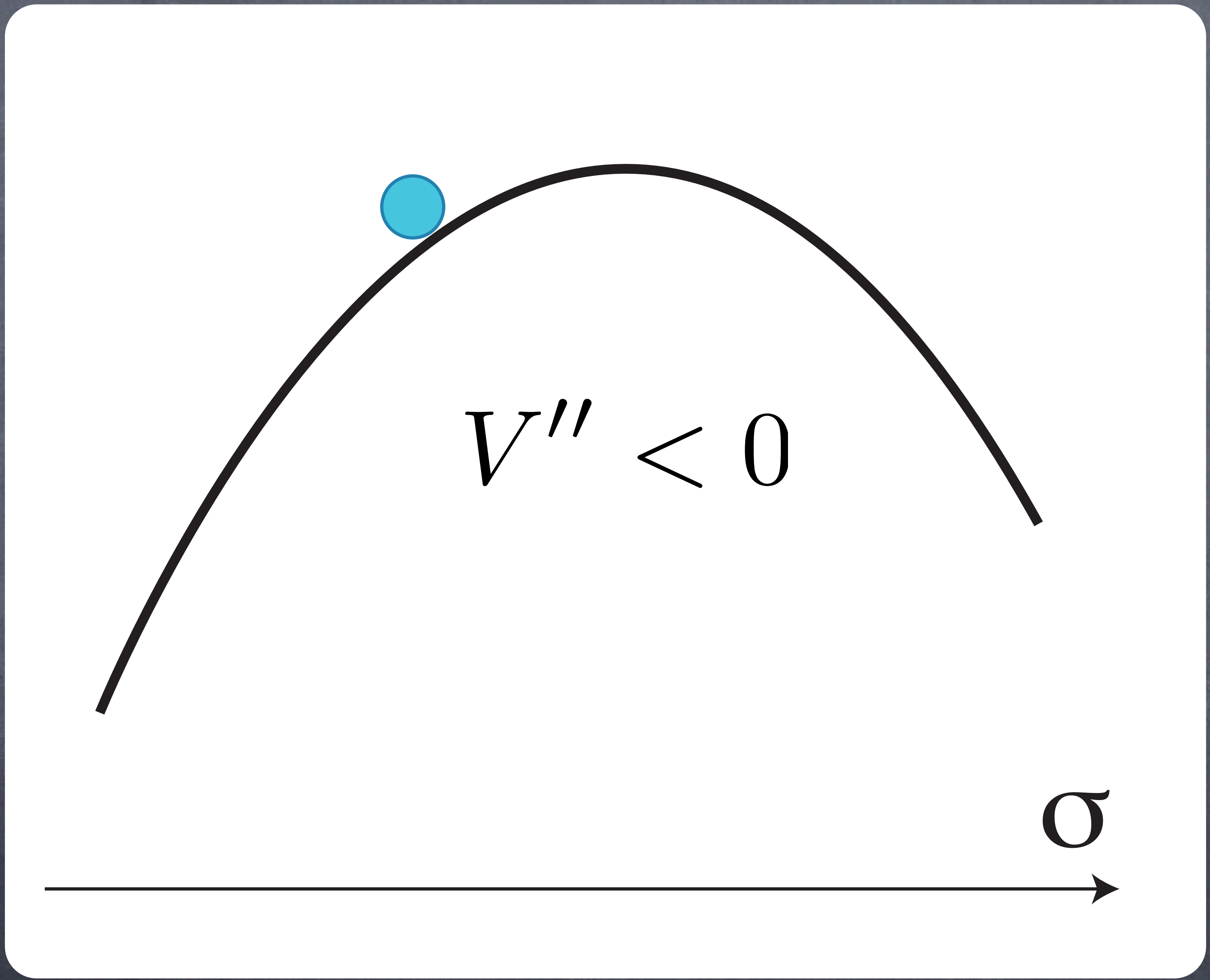
σ : curvaton

In order to obtain the red-tilted spectrum without relying on the inflation models, the curvaton must satisfy

$$\boxed{V''(\sigma_*) \simeq -\mathcal{O}(0.01) \times H_*^2}$$

Negative and (relatively) large mass!

The potential needs to be deviated from the quadratic potential!



Related works:
Enqvist and T.Takahashi `08, Enqvist et al `09, Kawasaki, Nakayama FT `09.

Hilltop curvaton

When one goes to the hilltop limit, the expression for the curvature perturbation is modified.

$$\zeta \sim c_1 \frac{\delta \rho_\sigma}{\rho_\sigma} - c_2 \frac{\delta H_{\rm osc}}{H_{\rm osc}}$$

Non-gaussianity increases mildly in the hilltop limit, and $f_{NL} >> 1$ is possible even if the curvaton dominates.

Kawasaki, Kobayashi, FT, 1107.6011

Hilltop curvaton

When one goes to the hilltop limit, the expression for the curvature perturbation is modified.

$$\boxed{\zeta \sim c_1 \frac{\delta\rho_\sigma}{\rho_\sigma} - c_2 \frac{\delta H_{\rm osc}}{H_{\rm osc}}}$$

non-uniform onset of oscillations

Non-gaussianity increases mildly in the hilltop limit, and $f_{NL} >> 1$ is possible even if the curvaton dominates.

Kawasaki, Kobayashi, FT, 1107.6011

Application to Nambu-Goldstone curvaton

$$\boxed{V(\sigma) = \Lambda^4 \left[1 - \cos\left(\frac{\sigma}{f}\right)\right]},$$

$$\Gamma_\sigma \sim \frac{1}{16\pi}\frac{m^3}{f^2} = \frac{1}{16\pi}\frac{\Lambda^6}{f^5};$$

We require

1) COBE normalization
2) Red-tilted spectrum $n_s = 0.96$

Then, the initial condition must be close to the hilltop, because otherwise the curvaton would start to oscillate soon after inflation.

(2) hilltop case

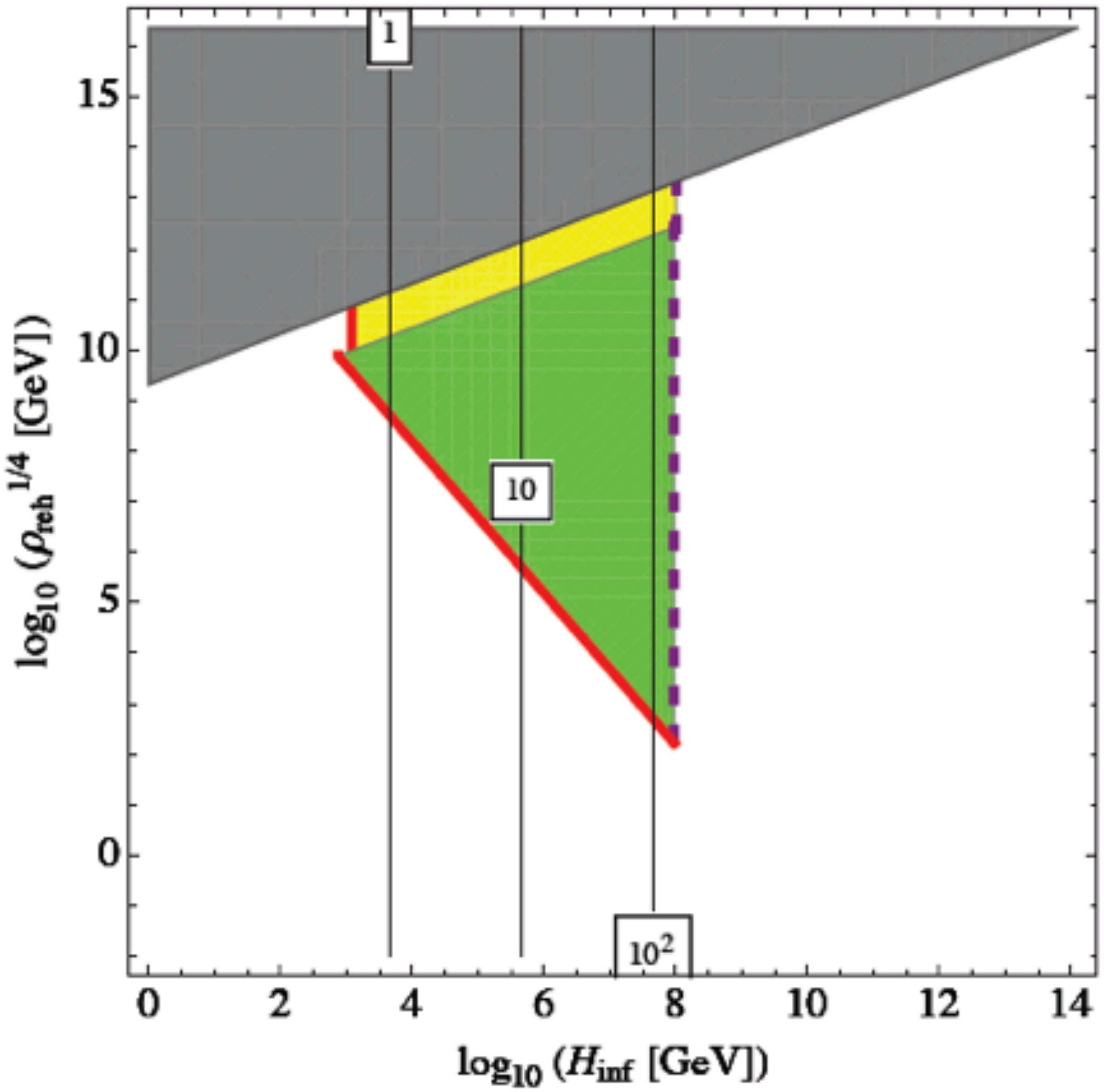


Figure 15: $\sigma_*/\pi f = 1 - 10^{-8}$, $r > 1$. $f_{\rm NL} \sim 20$ in most of the allowed region.

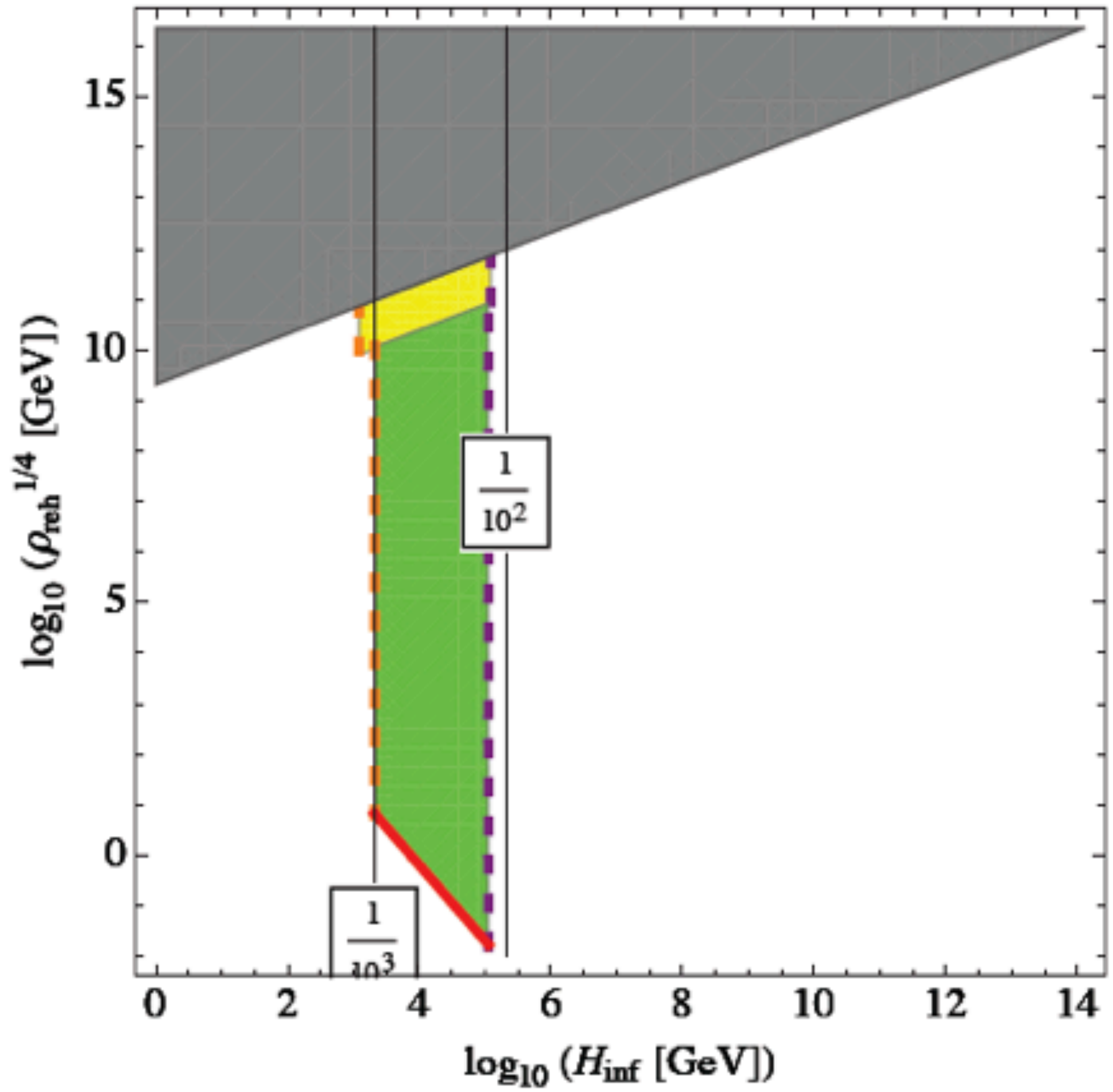


Figure 16: $\sigma_*/\pi f = 1 - 10^{-11}$, $r > 1$. $f_{\rm NL} \sim 30$ in most of the allowed region.

Prediction of 1107.6011

- In Nambu-Goldstone curvaton, f_{NL} is predicted to be in the range of 10 and 30.
- In particular, if we consider the moduli curvaton with the decay constant about 10^{17} - 10^{18} GeV, **f_{NL} should be about 30.**

N.B. : The curvaton is assumed to dominate the Universe at the decay, in contrast to the works in the past, and that is why this prediction is robust.
N.B.2 : The inflation is assumed to be not the chaotic one. So r <<< 0.1.

Conclusion

- Considering the 125GeV SM-like Higgs boson, the SUSY breaking scale at 10TeV - 1000TeV is attractive.
- Moduli problem is then relaxed, and successful cosmology becomes possible.
- Baryogenesis, dark matter, inflation model building are important remaining issues.
- Moduli curvaton predicts f_{NL} about 30.
- Moduli will be a probe of the high energy physics and early Universe!