Phenomenological Aspects of Polonyi/Moduli Problem

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Summer Institute 2011@ Fuji-Yoshida (2011/8/9)

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- Cosmological Polonyi/Moduli Problem
- Solutions to the Polonyi/Moduli problem
- 1. Heavy Moduli
- 2. Thermal inflation
- 3. Adiabatic mechanism

Hidden sector

- Hidden sector couples to SM sector only (nearly) gravitationally. (Polonyi / Moduli, ...)
- It may determine the structure of SM sector
- It cannot be produced by experiments
- However, it has significant effects on cosmology
- Probe/constrain hidden sector with cosmology

Polonyi field

- SUSY breaking field in gravity-mediation Z
- Super/Kahler potential

$$W = Z\mu^2 + W_0 \qquad K = |Z|^2$$

- Giving SUSY particle masses through

$$\mathcal{L} \sim \int d^2\theta \frac{Z}{M_P} W_a W^a \sim m_{\tilde{g}} \tilde{g}\tilde{g}$$

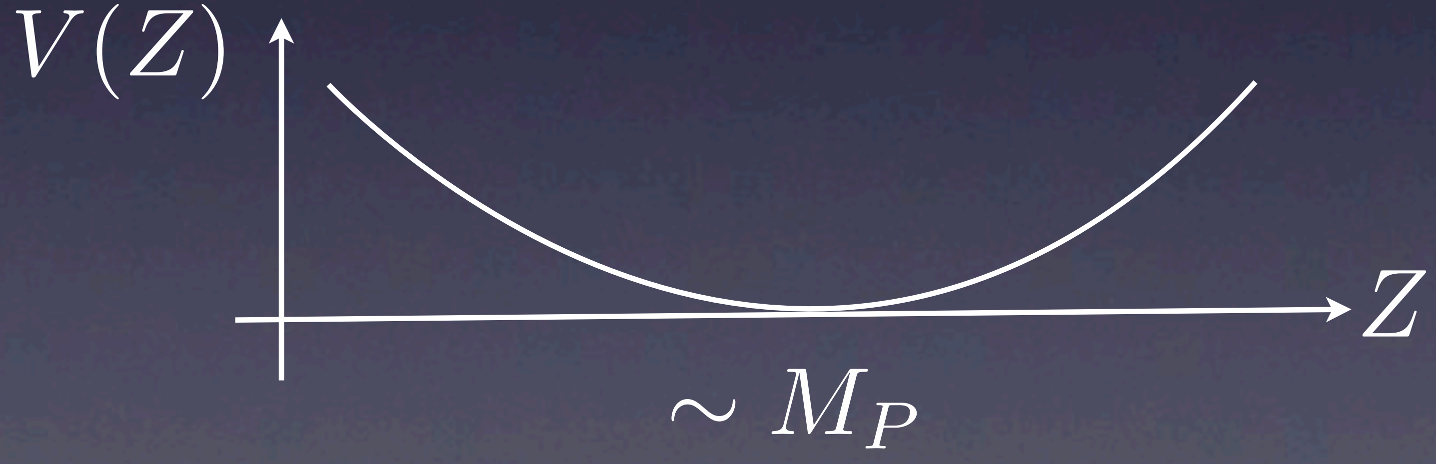
$$\mathcal{L} \sim \int d^4\theta \frac{Z^\dagger Z}{M_P^2} |f|^2 \sim m_{\tilde{f}}^2 |\tilde{f}|^2 \qquad m_{\tilde{g}} \sim m_{\tilde{f}} \sim \frac{F_Z}{M_P}$$

Polonyi potential

- Superpotential $W = Z\mu^2 + W_0$

  Kahler potential $K = |Z|^2$

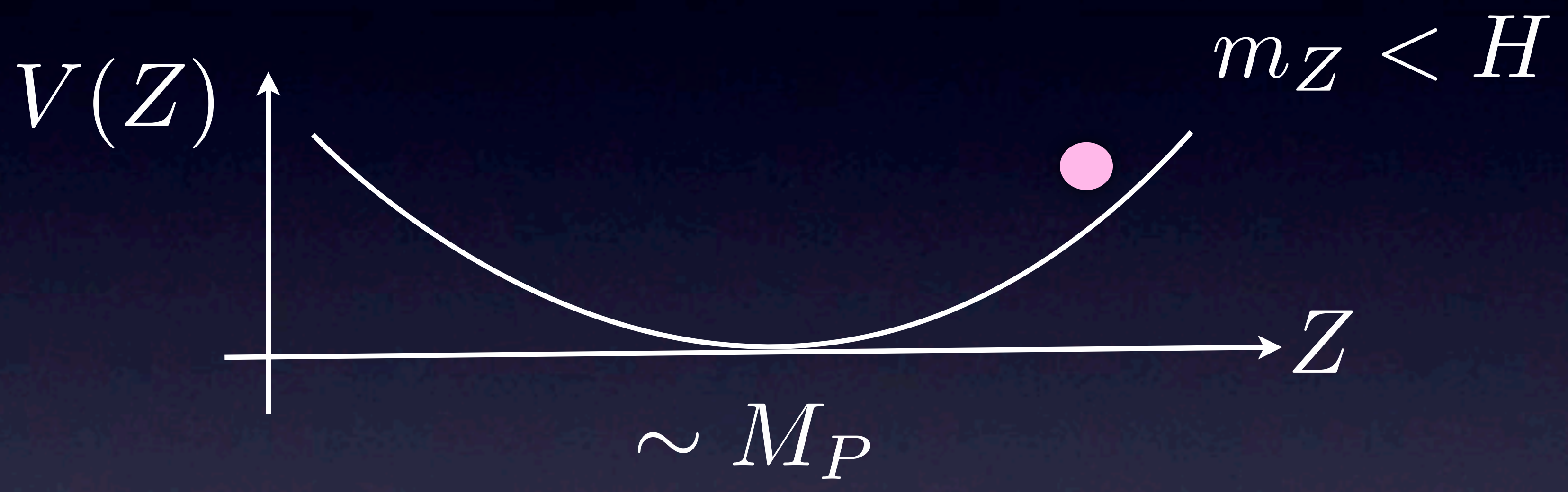
$$V = e^{K/M_P^2}\left[K^{i\bar{j}}(D_iW)(D_{\bar{j}}\bar{W}) - \frac{3|W|^2}{M_P^2}\right]$$



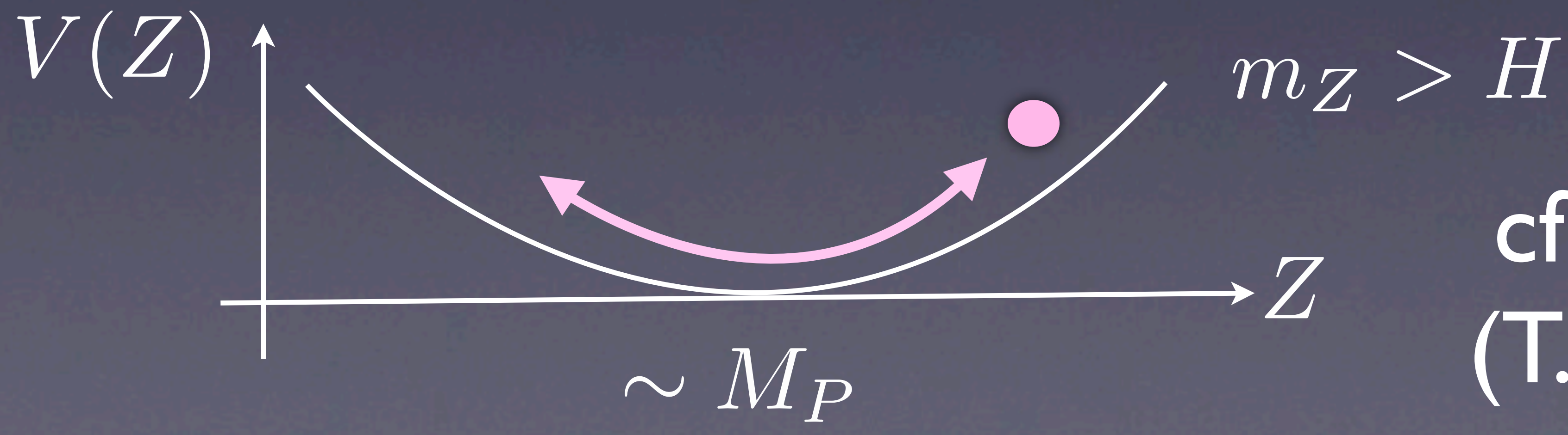
- Polonyi mass ~ gravitino mass $m_Z \sim m_{3/2}$

Polonyi Problem

- During inflation, Polonyi is placed anywhere



- At H~m, Polonyi begins to oscillate around minimum with typical amplitude $\sim M_P$



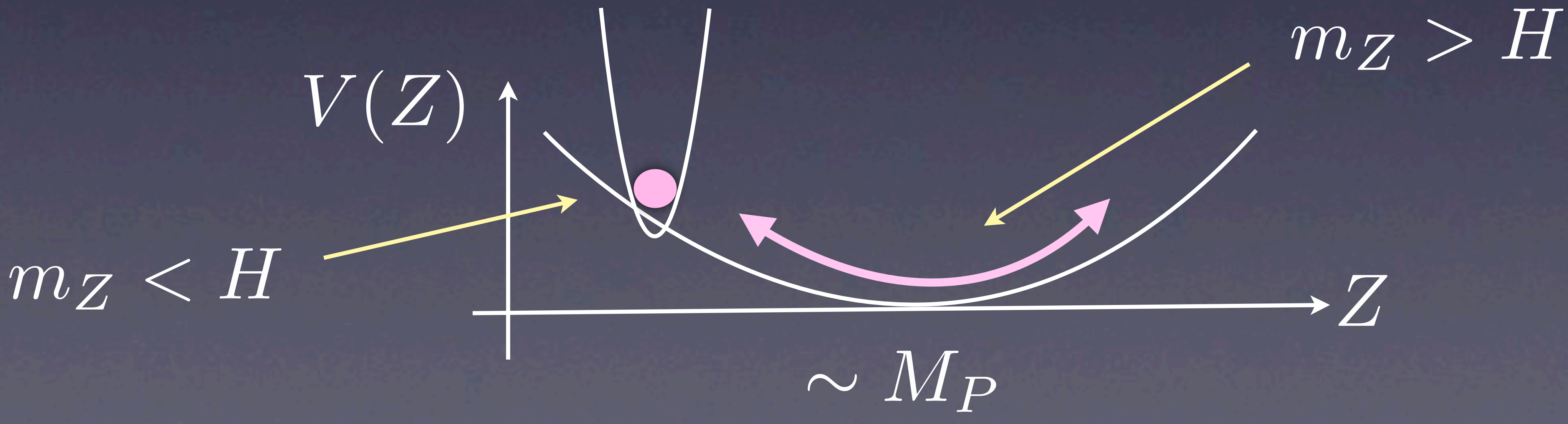
cf. curvaton
(T.Takahashi)

Polonyi Problem

- The situation is same if the Polonyi has Hubble mass

$$K \sim \frac{1}{M_P^2}|Z|^2|I|^2 \rightarrow -\mathcal{L} \sim H^2|Z|^2 \qquad I : \text{inflaton}$$

- Polonyi begins oscillation at H~m with amplitude ~MP



Polonyi Problem

- Polonyi lifetime

[Coughlan et al. (1983), Ellis et al. (1986), Goncharov et al. (1986)]

$$\tau_Z \sim \left(\frac{m_Z^3}{M_P^2}\right)^{-1} \sim 10^4\mathrm{sec}\left(\frac{1\mathrm{TeV}}{m_Z}\right)^3$$

- Polonyi abundance

T_R :reheat temperature

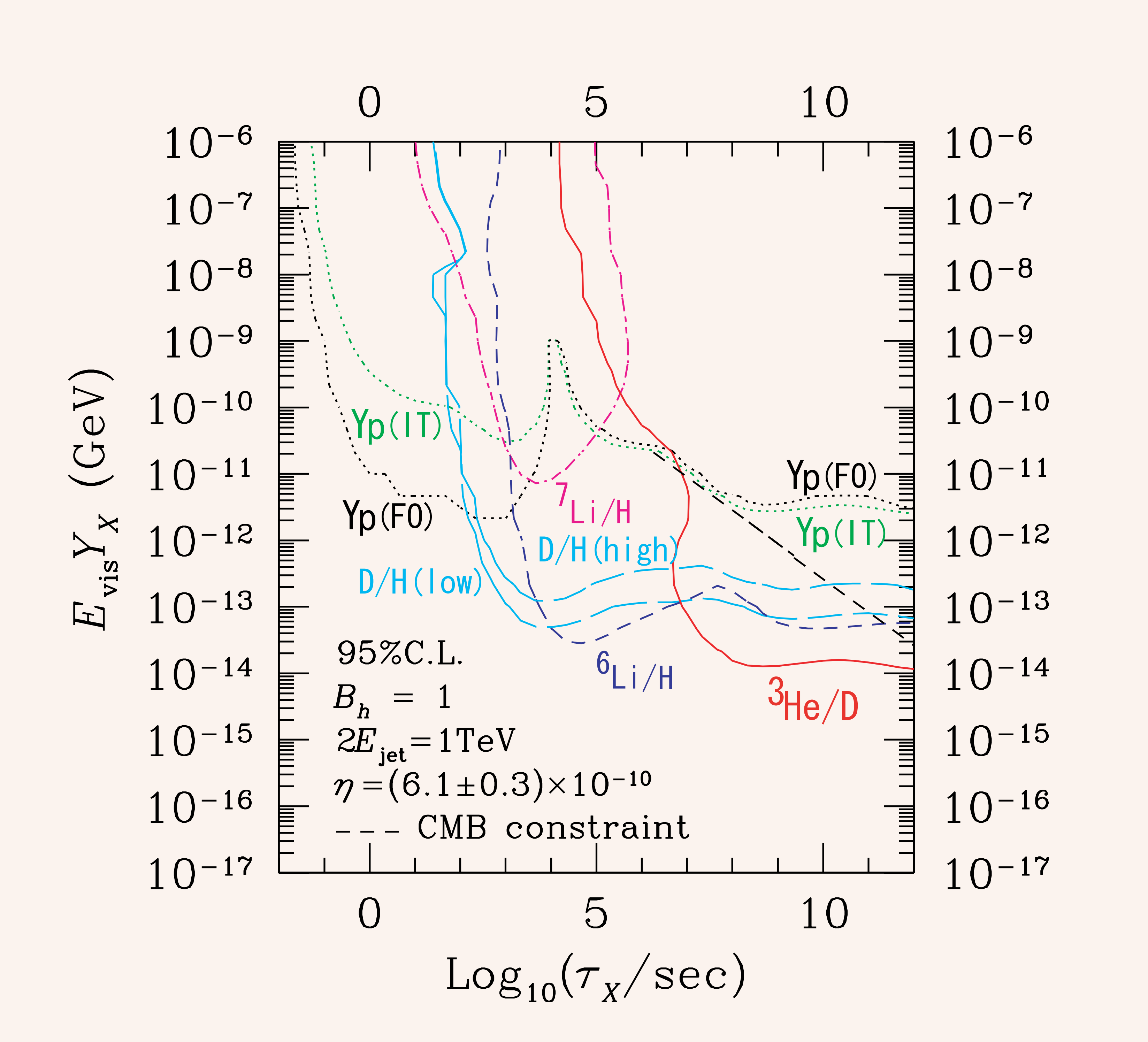
$$\frac{\rho_Z}{s} = \frac{1}{8}T_R\left(\frac{Z_i}{M_P}\right)^2 \sim 10^5\mathrm{GeV}\left(\frac{T_R}{10^6\mathrm{GeV}}\right)$$

- Big bang nucleosynthesis constraint

$$\frac{\rho_Z}{s} \lesssim 10^{-14}\mathrm{GeV}$$

Polonyi Problem !

Constraint on energy injection from BBN



[Kawasaki, Kohri, Moroi (2005)]

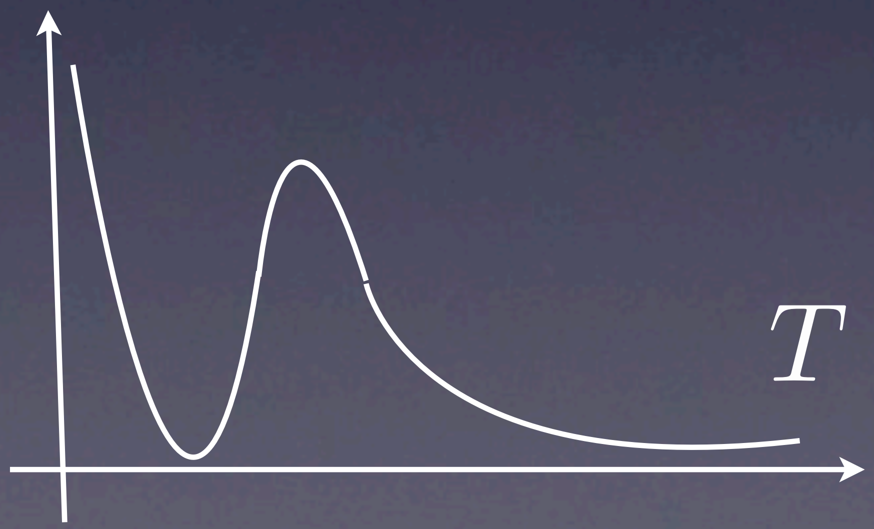
Moduli Problem

- Light scalar field in compactification of extra dimensions in String theory
- E.g. Kahler moduli in KKLT stabilization in type IIB string theory

$$K = -3\ln(T + T^\dagger)$$

$$W = W_0 - Ae^{-aT}$$

$$\longrightarrow \quad m_Z^2 \sim (8\pi^2) m_{3/2}^2$$



Moduli Problem

- Gravitational coupling

$$K = \frac{1}{M_P^2}|\Phi|^2|Z|^2 \qquad \Phi \ : \ \text{SUSY breaking field}$$

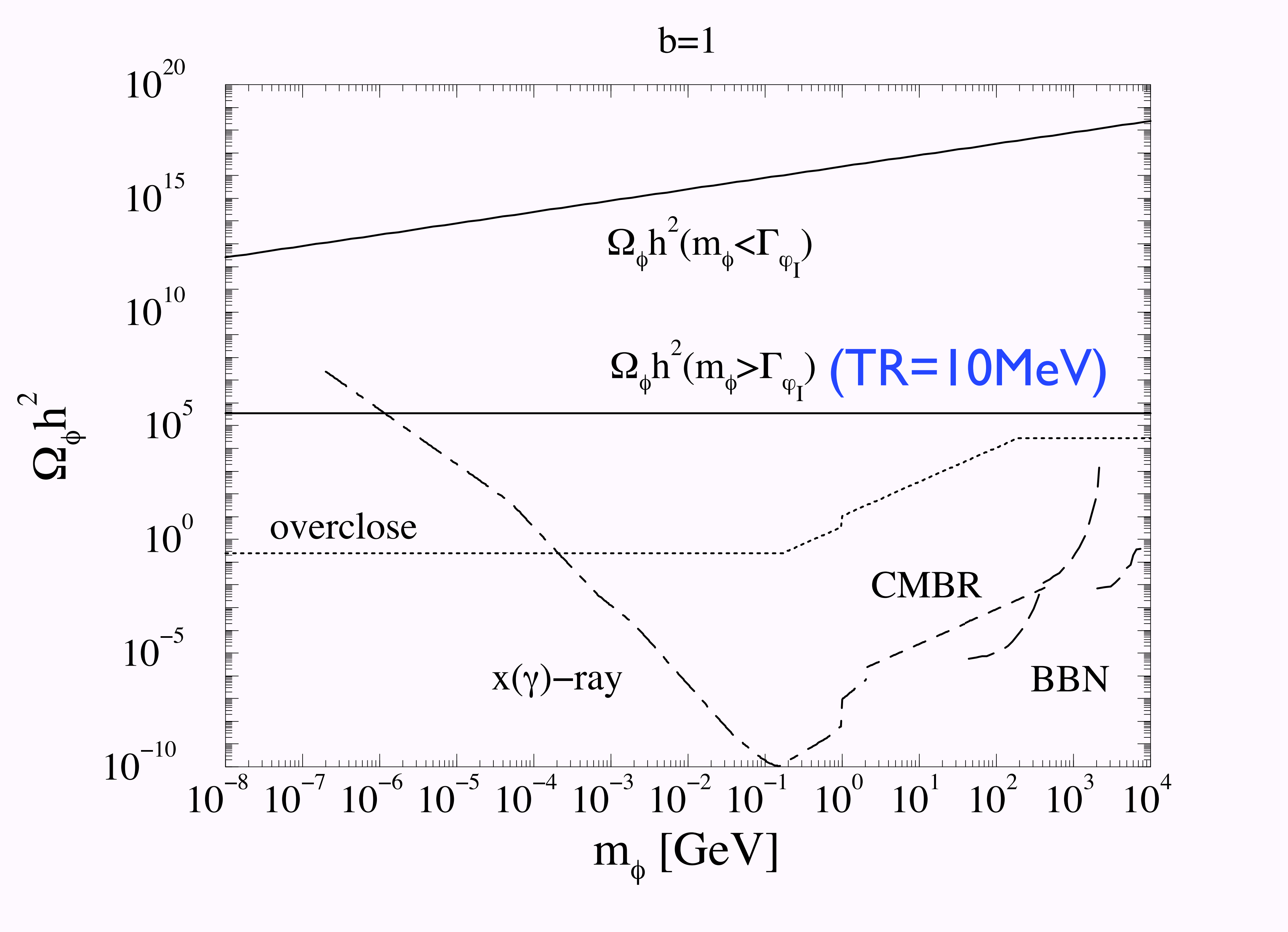
$$\longrightarrow \quad V \sim \frac{F_\Phi^2}{M_P^2}|Z|^2 \sim m_{3/2}^2 M_P^2 \quad \longrightarrow \quad m_Z \sim m_{3/2}$$

- Cosmological effects similar to the Polonyi

Cosmological Polonyi/Moduli Problem

[Banks et al. (1983), de Carlos et al. (1993)]

Constraint on the modulus abundance



[Asaka, Kawasaki (1999)]

Solutions

- 1. Moduli is heavy enough to decay before BBN
- 2. Thermal inflation for diluting moduli
- 3. Adiabatic suppression mechanism

1. Heavy Moduli

Heavy moduli

- The moduli lifetime $\tau_Z \sim \left(\frac{m_Z^3}{M_P^2}\right)^{-1} \sim 10^4 \mathrm{sec} \left(\frac{1\mathrm{TeV}}{m_Z}\right)^3$

$m_Z > 100\mathrm{TeV} \longrightarrow \tau_Z \ll 1\mathrm{sec}$: no BBN bound

- Typically, $m_Z \sim m_{3/2}$ (gravitino mass)

$m_{3/2} \ll 100\mathrm{GeV}$: gauge-mediation

$m_{3/2} \sim 1\mathrm{TeV}$: gravity-mediation

$m_{3/2} \gtrsim 100\mathrm{TeV}$: anomaly-mediation

: mirage-mediation

Setup of Mirage-mediation

T : moduli Φ_i : MSSM fields

$$K = -3\ln(T+T^*) + \Phi_i^*\Phi_i$$

$$W = w_0 - Ae^{-aT} + \frac{\lambda_{ijk}}{6}\Phi_i\Phi_j\Phi_k$$

The vacuum is AdS.

- Add extra uplifting term

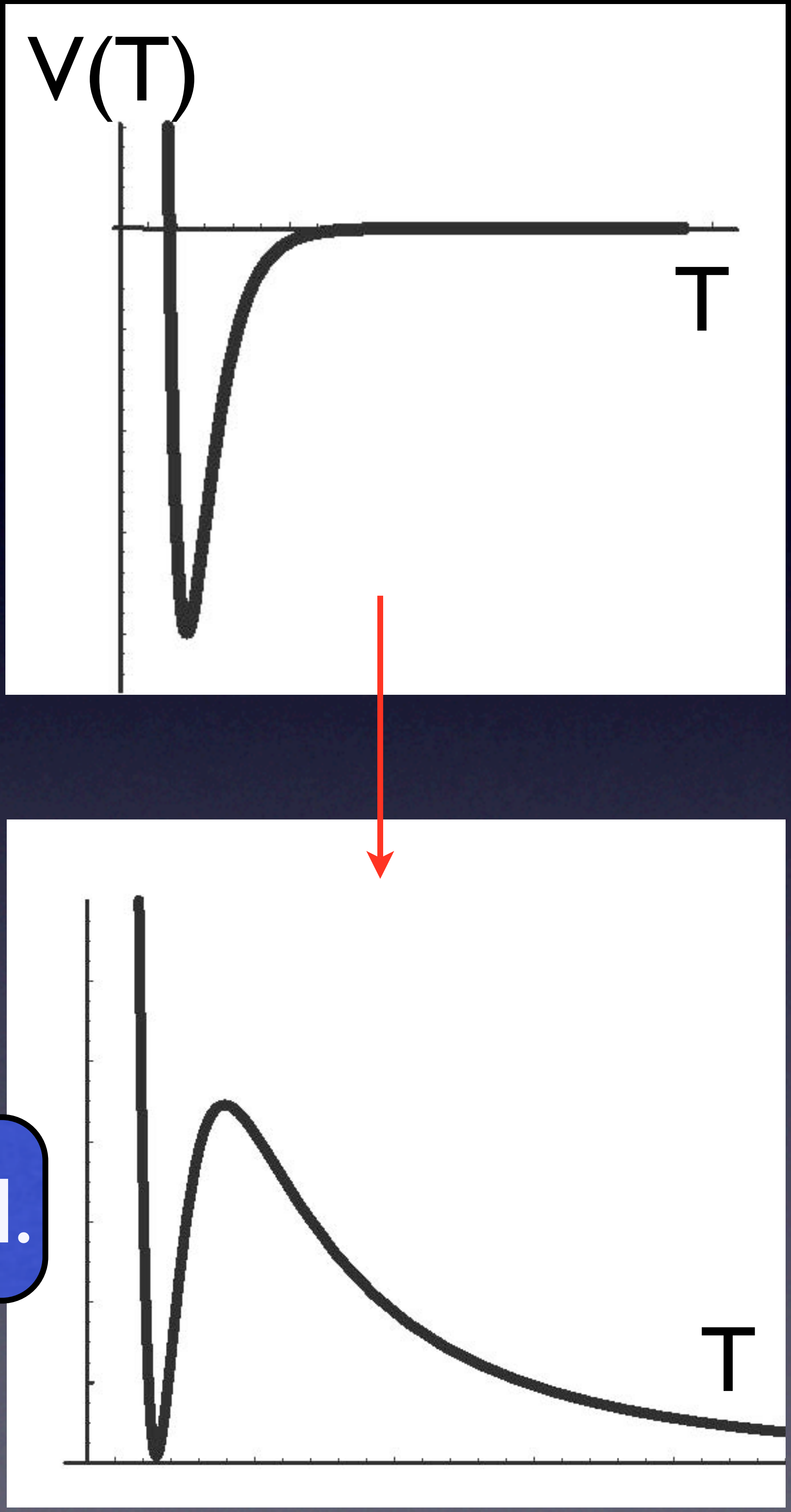
(KKLT-type moduli stabilization)

$$V_{\mathrm{lift}} = \frac{D}{(T+T^*)^m}$$

Positive vacuum energy can be obtained.

→ Source of SUSY breaking

Modulus potential



SUSY breaking

- $F_T \neq 0$ at dS minimum
- Uplifting to break SUSY

↓

$\longrightarrow$ Modulus mediation ~ Anomaly mediation

$$m_{\rm SUSY} \sim \boxed{\frac{F_T}{T}} \sim \boxed{\frac{1}{8\pi^2}\frac{F_{\rm total}}{M_P}}$$

e.g., Gaugino mass : $M_a = \boxed{M_0} + \boxed{\frac{m_{3/2}}{16\pi^2} b_a g_a^2}$

Mixed-modulus-anomaly mediation

Choi et al (04), Endo et al (05), Choi, Jeong and Okumura (05)

$$m_{3/2} \sim (8\pi^2) m_{\rm SUSY} \gg 1{\rm TeV}$$ Heavy gravitino

$$m_T \sim (8\pi^2) m_{3/2} \sim O(10^3){\rm TeV}$$ Heavy moduli

⟹ Heavy moduli significantly affect cosmology.

Heavy moduli scenario

- The moduli reheats the Universe with ~ MeV
- LSP overproduction problem

$$\Gamma(Z \to gg) \sim \Gamma(Z \to \tilde{g}\tilde{g}) \sim \frac{m_Z^3}{M_P^2}$$ [M.Endo, F.Takahashi (2008)]

$$\frac{\rho_{\rm LSP}}{s} \sim \frac{m_{\rm LSP}}{m_Z} T_Z \sim 10^{-6}{\rm GeV}\left(\frac{m_{\rm LSP}}{100{\rm GeV}}\right) \gg \underset{\uparrow}{4 \times 10^{-10}}{\rm GeV}$$

DM bound

- Dilute baryon asymmetry by the moduli decay

Heavy moduli scenario

- Moduli may be much heavier than gravitino

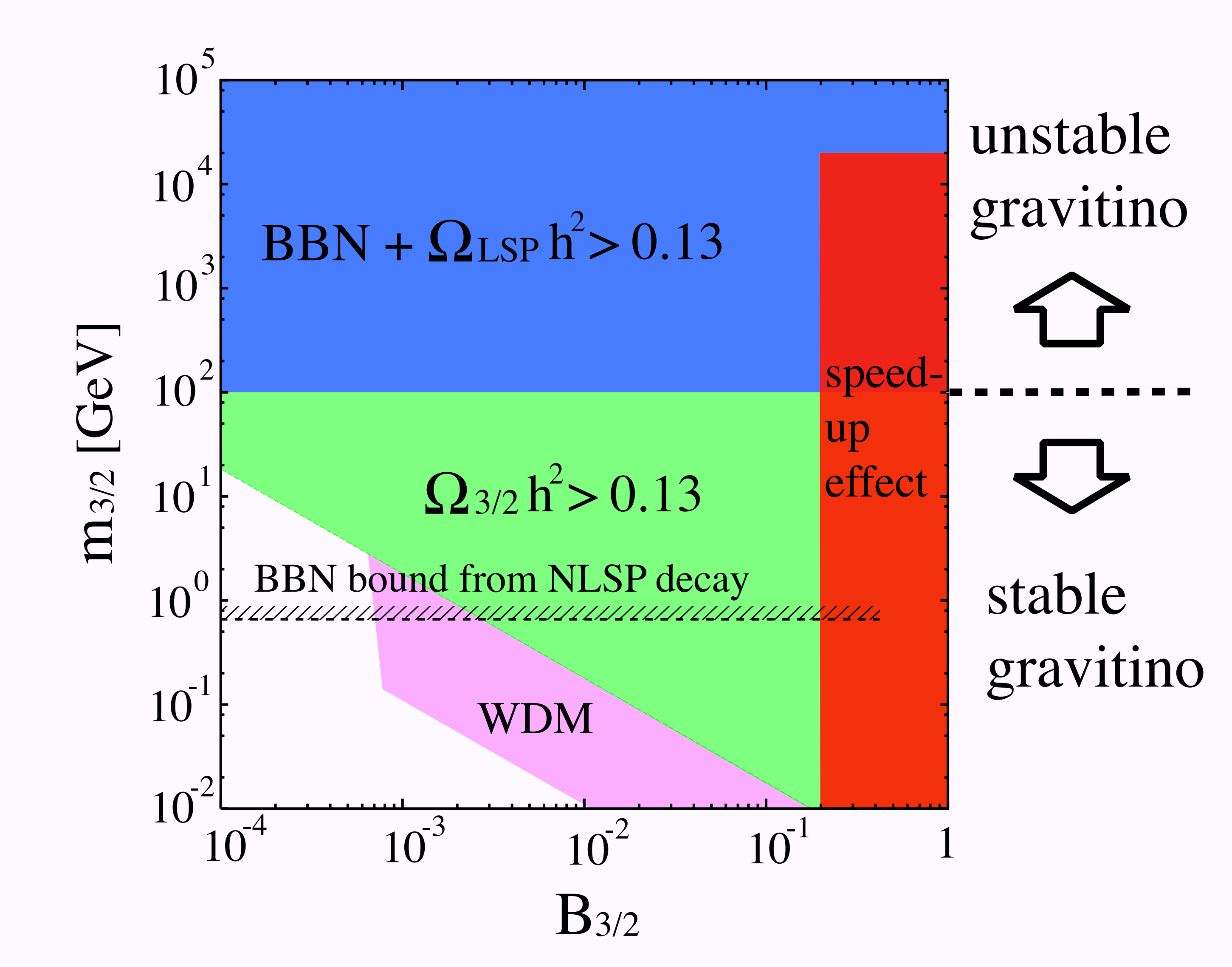
$m_Z \sim (8\pi^2) m_{3/2} \sim 10^3 \mathrm{TeV}$: mirage-mediation

- Gravitino production from moduli

$$B_{3/2} = \frac{\Gamma(Z \to \psi_{3/2})}{\Gamma_Z}$$

$$\sim O(0.1)$$

[M.Endo, K.Hamaguchi, F.Takahashi (2006), S.Nakamura, M.Yamaguchi (2006)]



Baryon asymmetry

- Create enough asymmetry which survives dilution after moduli decay
- Affleck-Dine mechanism is perhaps the only way

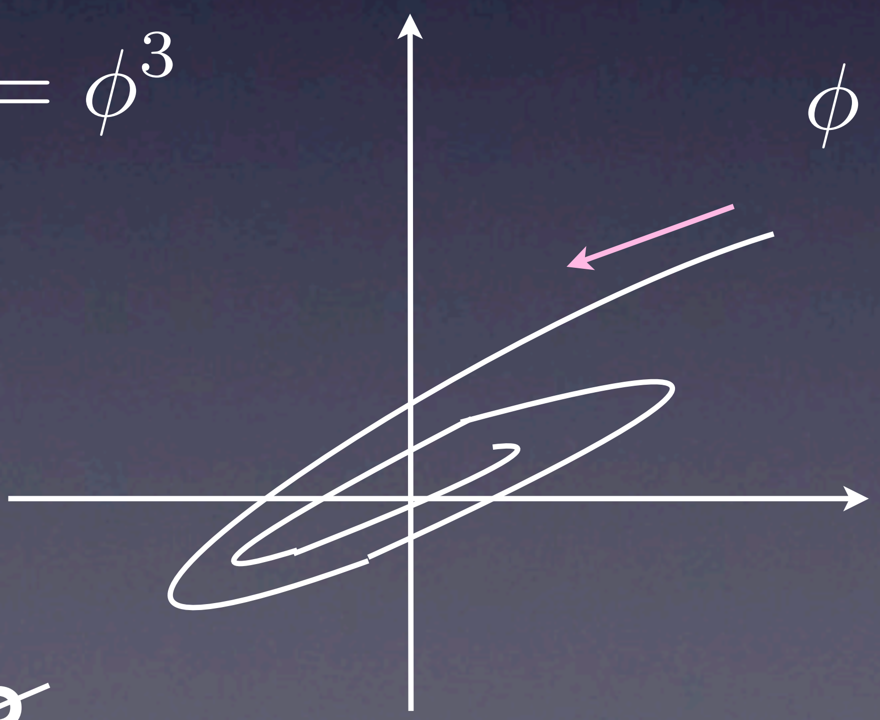
ϕ :AD field with baryon/lepton number

$$\text{e.g.,}\ (LH_u) = \phi^2,\ (udd) = \phi^3$$

$$\boxed{n_B = i(\dot{\phi}\phi^* - \dot{\phi}^*\phi) = |\phi|^2\dot{\theta}}$$

$$W = \frac{(LH_u)^2}{M} \rightarrow V_A = A\frac{\phi^4}{M} + \text{h.c.}$$

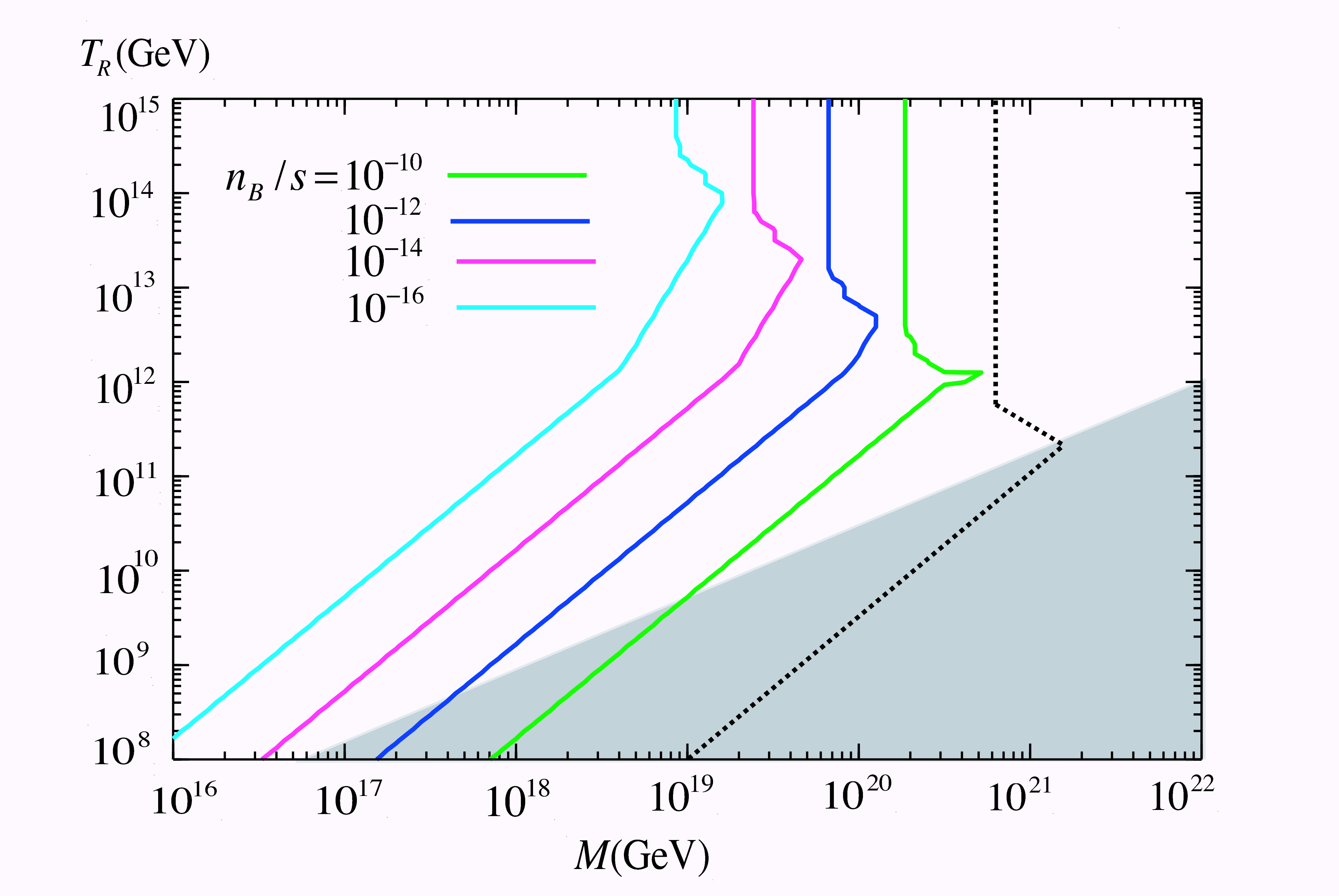
~~Baryon~~, ~~CP~~



- AD baryogenesis

through (udd) or (LLe) flat direction

$$W = \frac{1}{M^3}(udd)^2, \frac{1}{M^3}(LLe)^2$$



[Kawasaki, KN (2006)]

Summary of heavy moduli

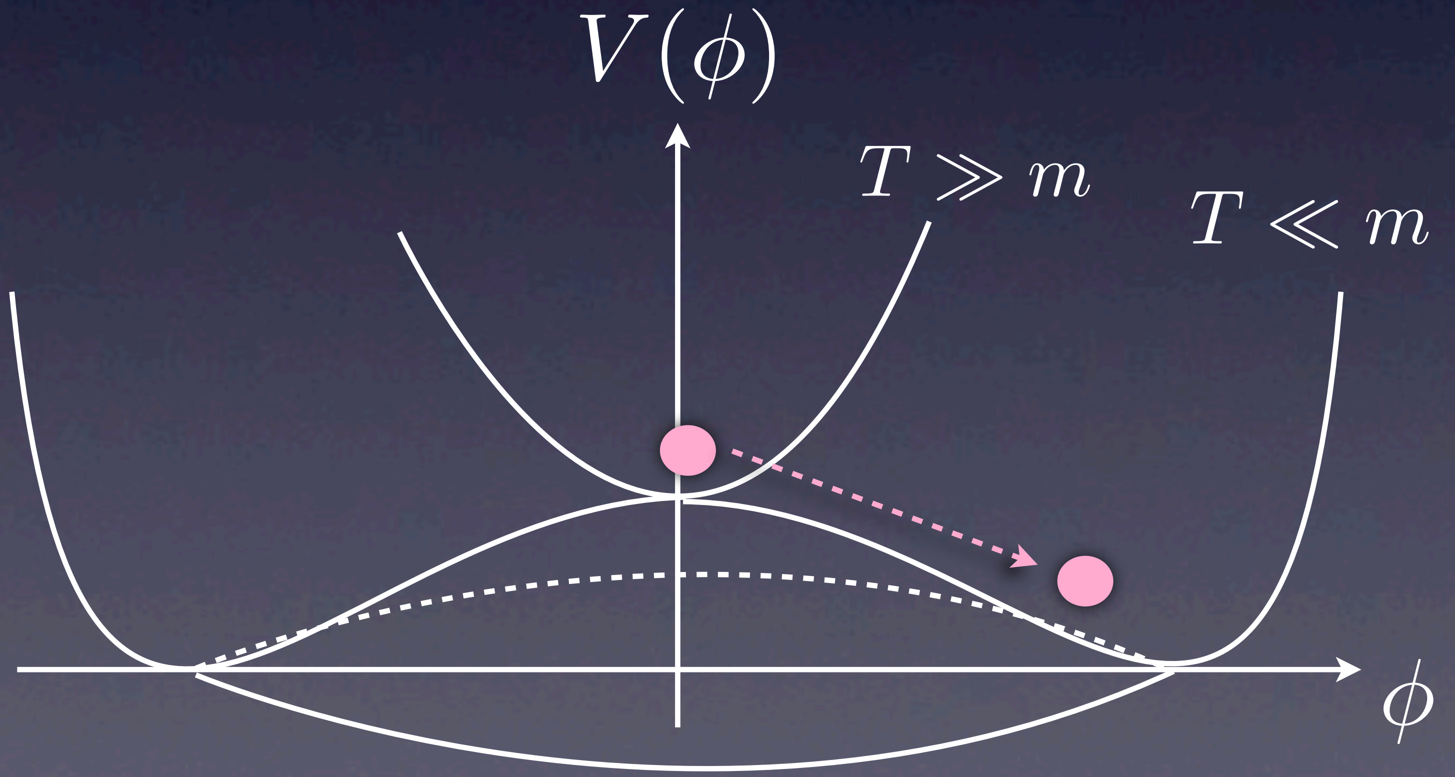
- Moduli heavier than 100TeV avoids BBN constraint.
- Anomaly- or Mirage-mediation predict heavy mass.
- LSP/Gravitino production from moduli decay is problematic.
- R-parity violation may be needed.
- Baryon asymmetry is diluted. Affleck-Dine mechanism may create enough asymmetry.

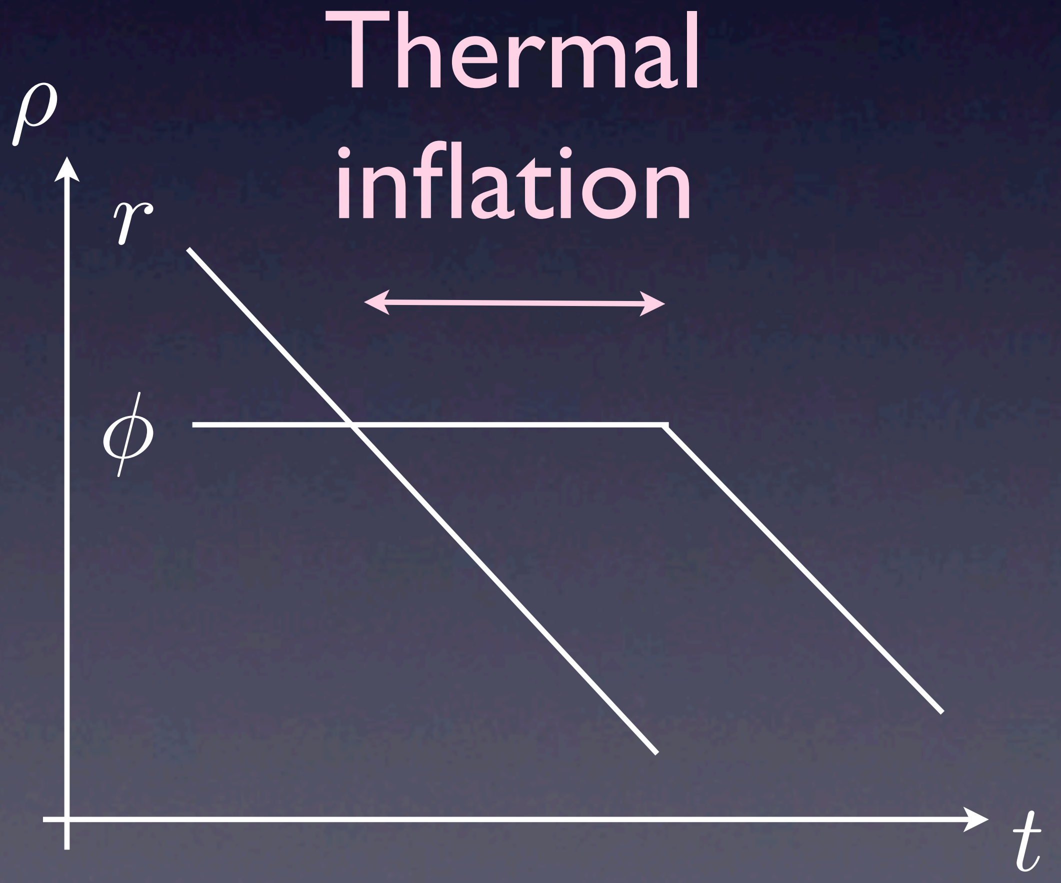
2. Thermal inflation

Thermal inflation

- Late time inflation caused by “Flaton” field
- Moduli are diluted by thermal infaltion

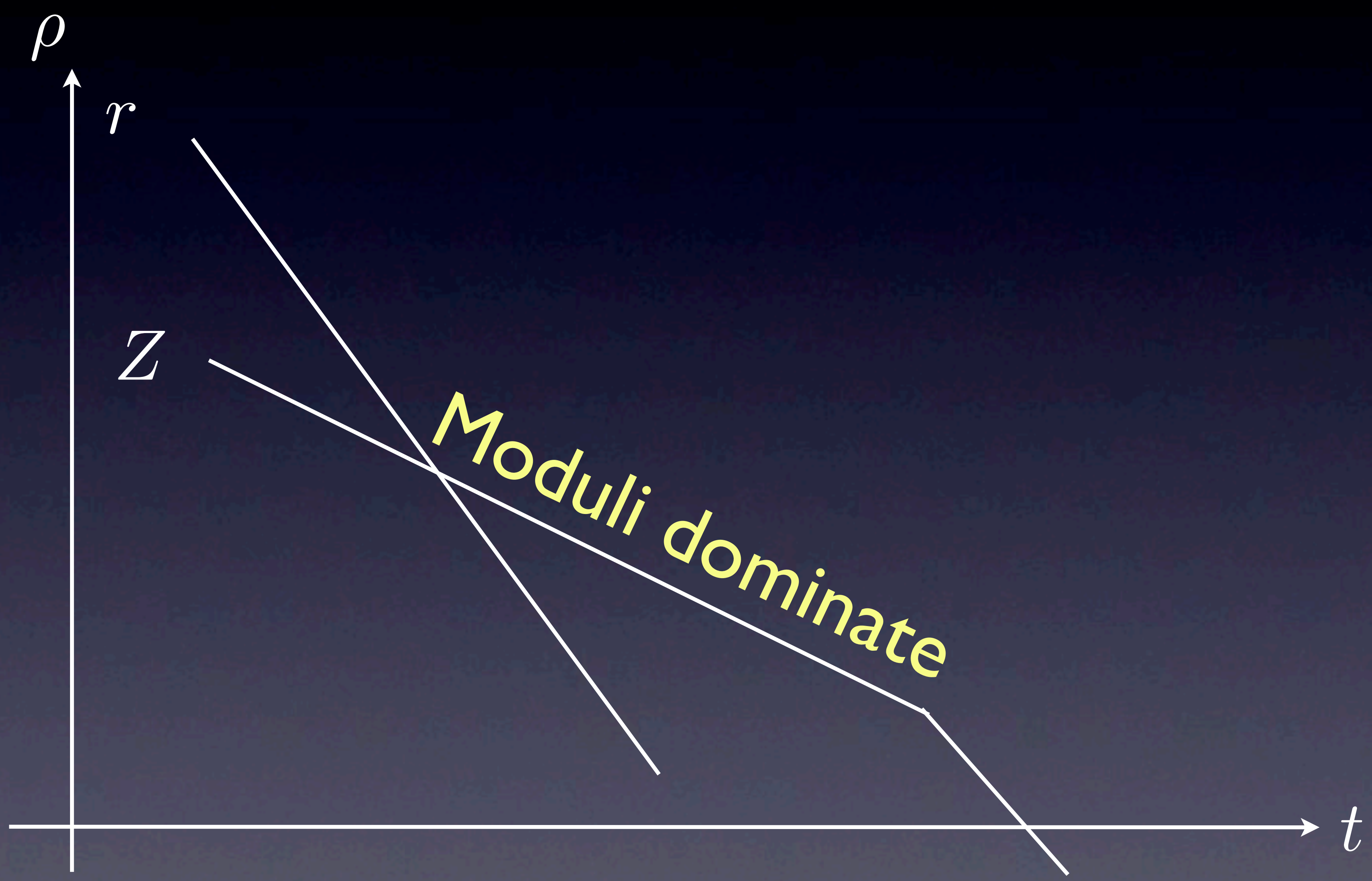
$$V \sim V_0 + (T^2 - m^2)|\phi|^2 + |\phi|^n$$



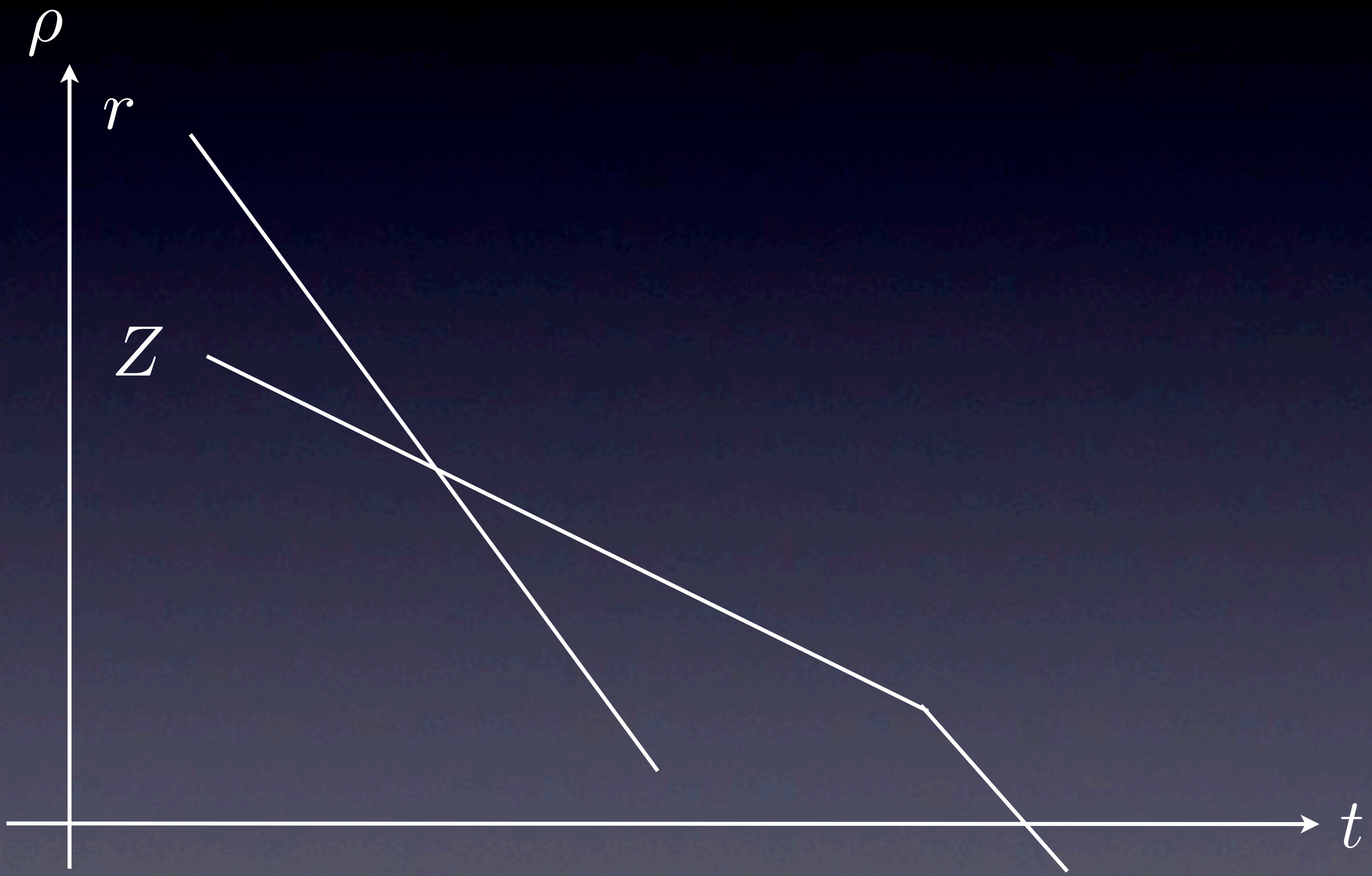


[K.Yamamoto (1985), Lazarides et al (1986), Lyth, Stewart (1995)]

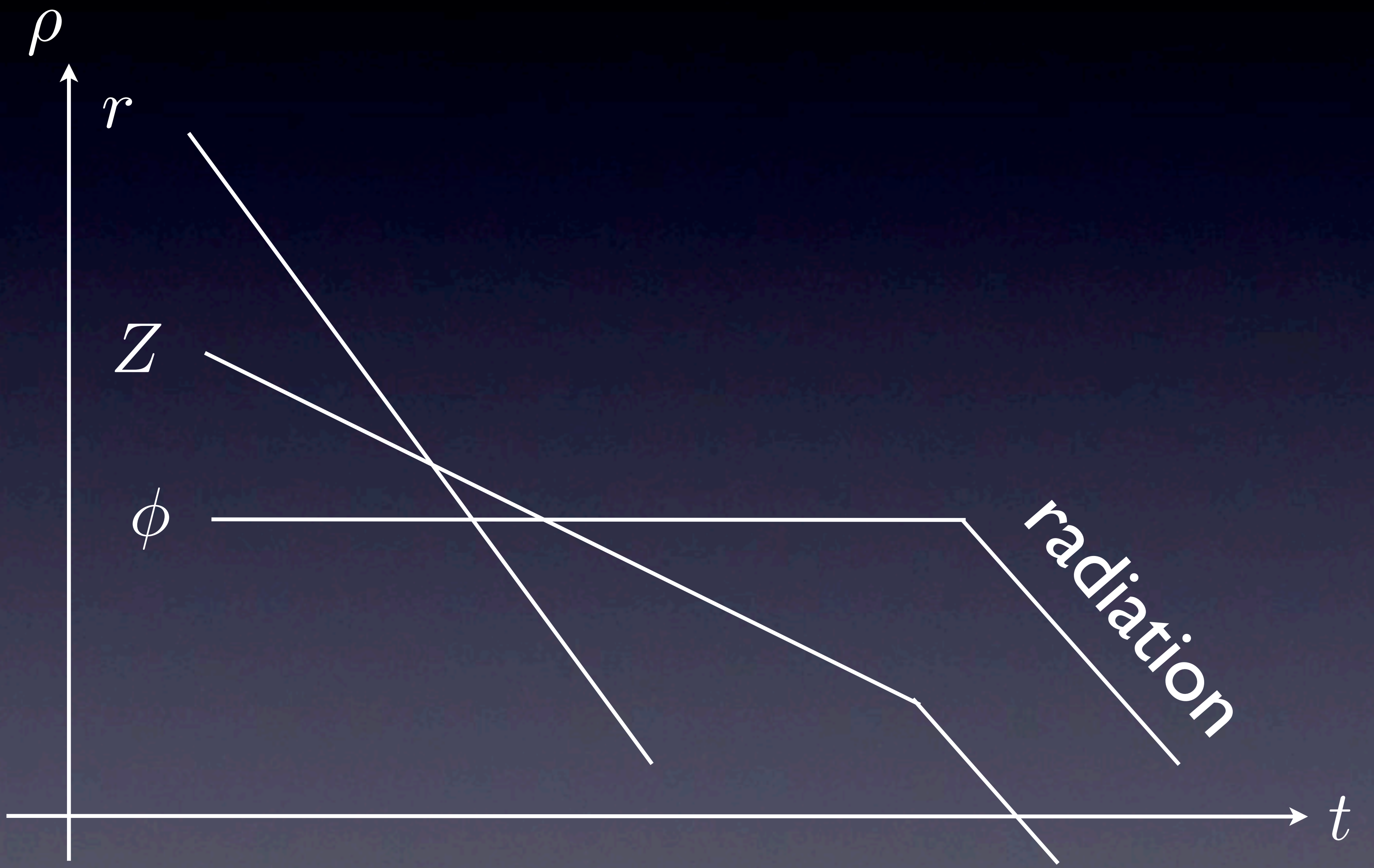
Suppressing moduli



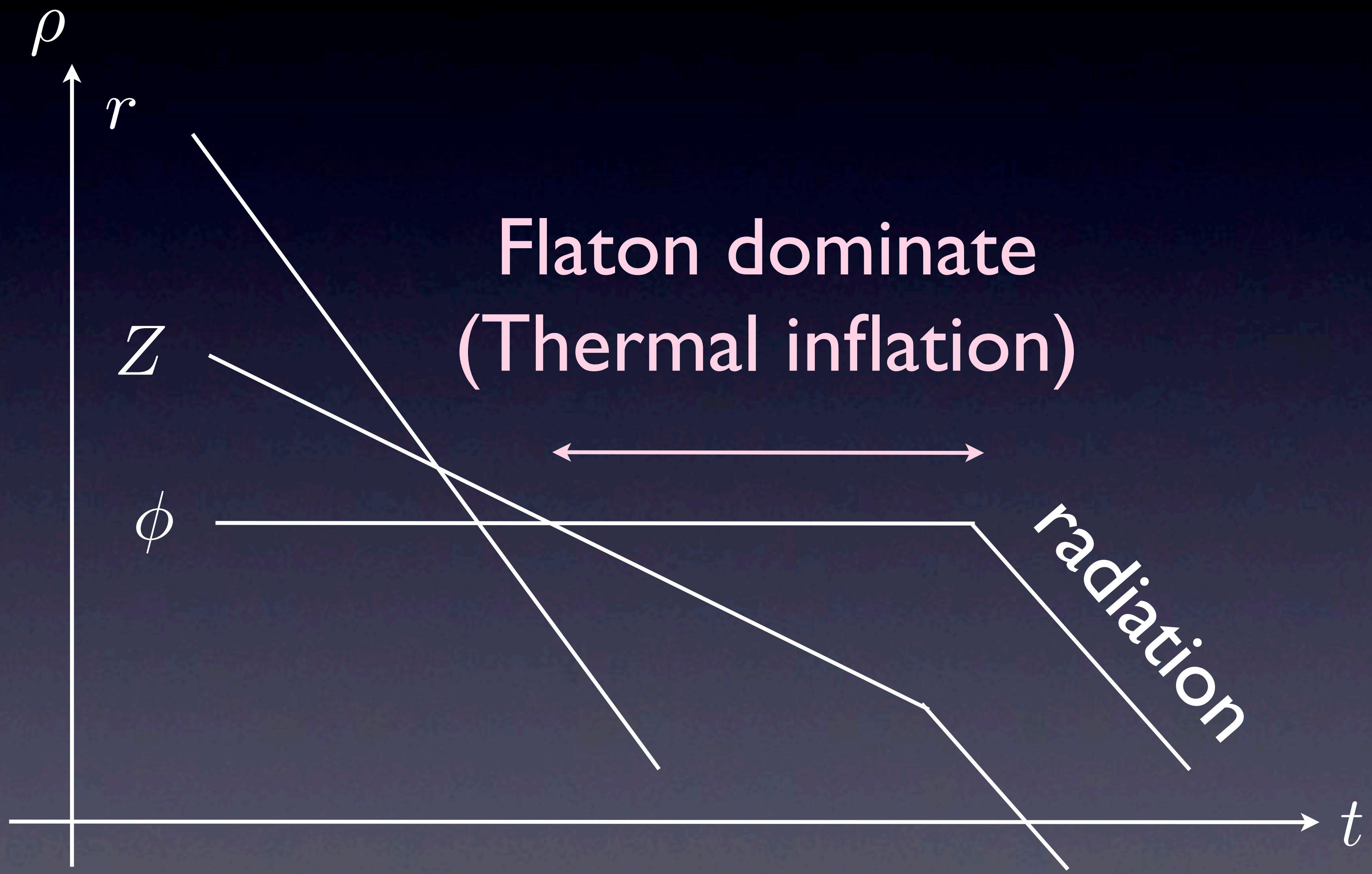
Suppressing moduli



Suppressing moduli

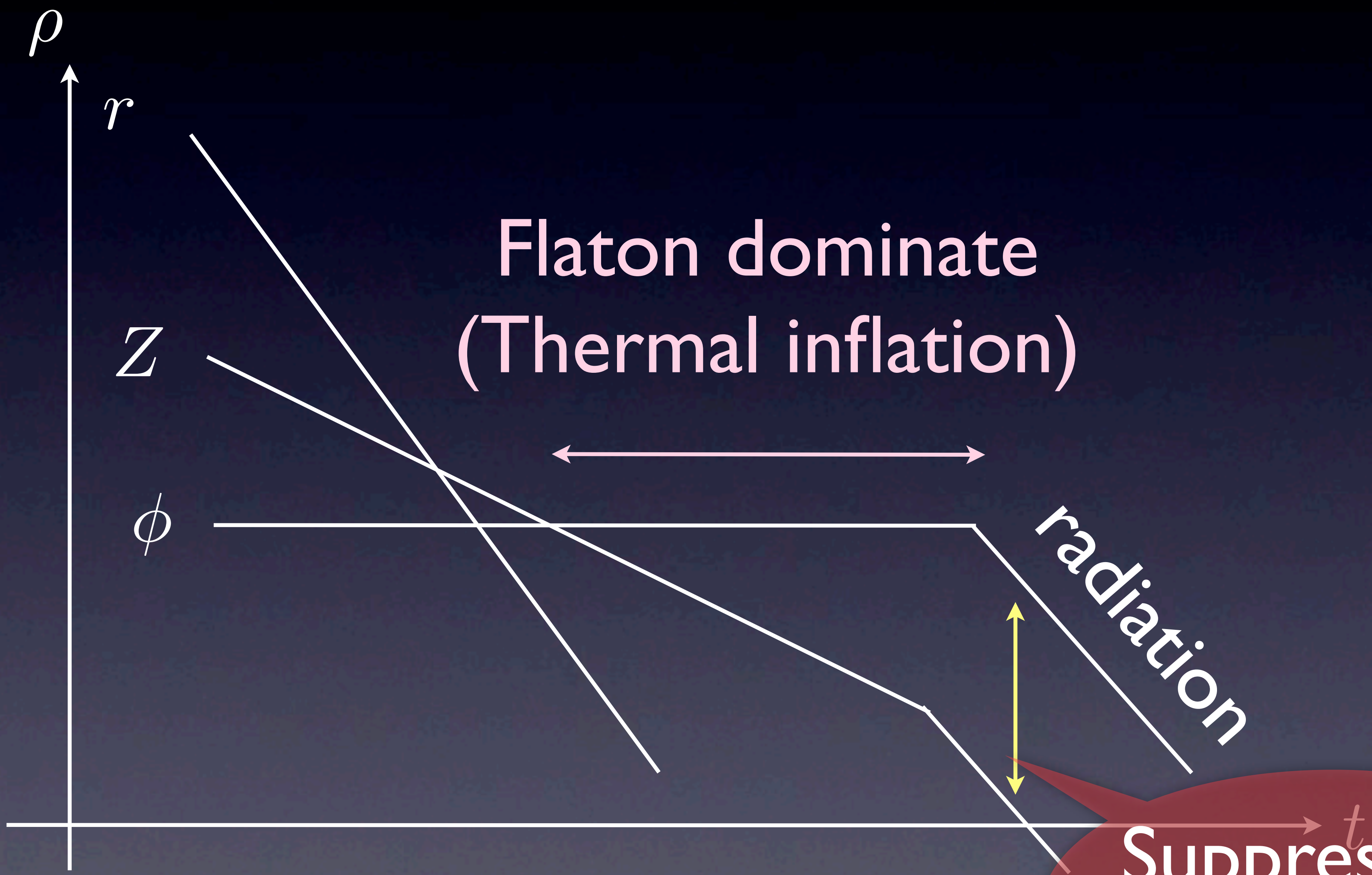


Suppressing moduli



Flaton dominate
(Thermal inflation)

Suppressing moduli



Flaton dominate
(Thermal inflation)

Suppression
of moduli

Suppressing moduli

- Flaton domination (thermal inflation)

  starts at $T \sim V_0^{1/4}$

- Thermal inflation ends at $T \sim m$

- Duration of thermal inflation : $e^N \sim V_0^{1/4}/m$

$$m \sim 1\mathrm{TeV}, \langle\phi\rangle \sim 10^{10}\mathrm{GeV} \rightarrow e^N \sim 10^3$$

- Moduli abundance is suppressed by $e^{3N} \sim 10^9$

- Flaton decay reheats the Universe

$$\Gamma_\phi \sim \frac{m_\phi^3}{\langle\phi\rangle^2} \rightarrow T_\phi \sim \sqrt{\Gamma_\phi M_P} \sim O(1)\mathrm{GeV}$$

Thermal inflation model

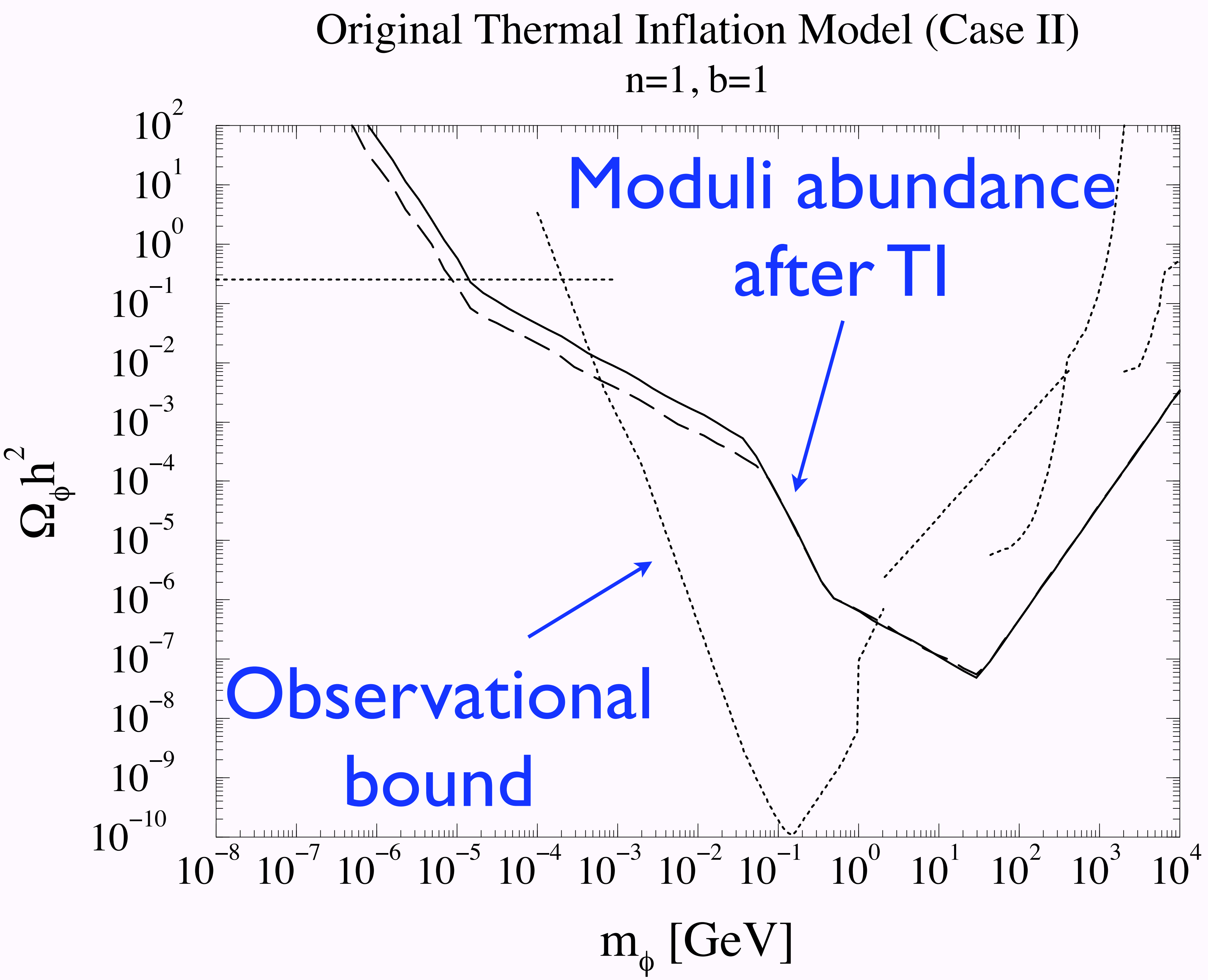
- The flaton superpotential (Z_n symmetry)

$$W = \frac{\phi^n}{nM^{n-3}} + k\phi Q\bar{Q} + W_0.$$

- The flaton scalar potential

$$V = V_0 - m^2|\phi|^2 + (n-3)\left(\frac{A\phi^n}{nM^{n-3}} + \text{h.c.}\right) + \frac{|\phi|^{2(n-1)}}{M^{2(n-3)}}.$$

- Heavy quark Q are massless at phi = 0 and they are in thermal bath.



Moduli abundance after TI

Observational bound

[Asaka, Kawasaki (1999)]

Problems with TI

- The flaton superpotential (Z_n symmetry)

$$W = \frac{\phi^n}{nM^{n-3}} + k\phi Q\bar{Q} + W_0.$$

- Z_n symmetry is spontaneously broken after TI

  → Domain walls appear after thermal inflation

- Thermal inflation also dilutes the baryon asymmetry.

  → How to create baryon asym. after TI ?

Unstable DW

- Introduce explicit Z_n breaking terms

$W = \epsilon\phi^\ell / M^{\ell-3}$ $\longrightarrow$ DWs becomes unstable

- Even without such a term, DW is unstable because

Z_n symmetry is anomalous at the quantum level

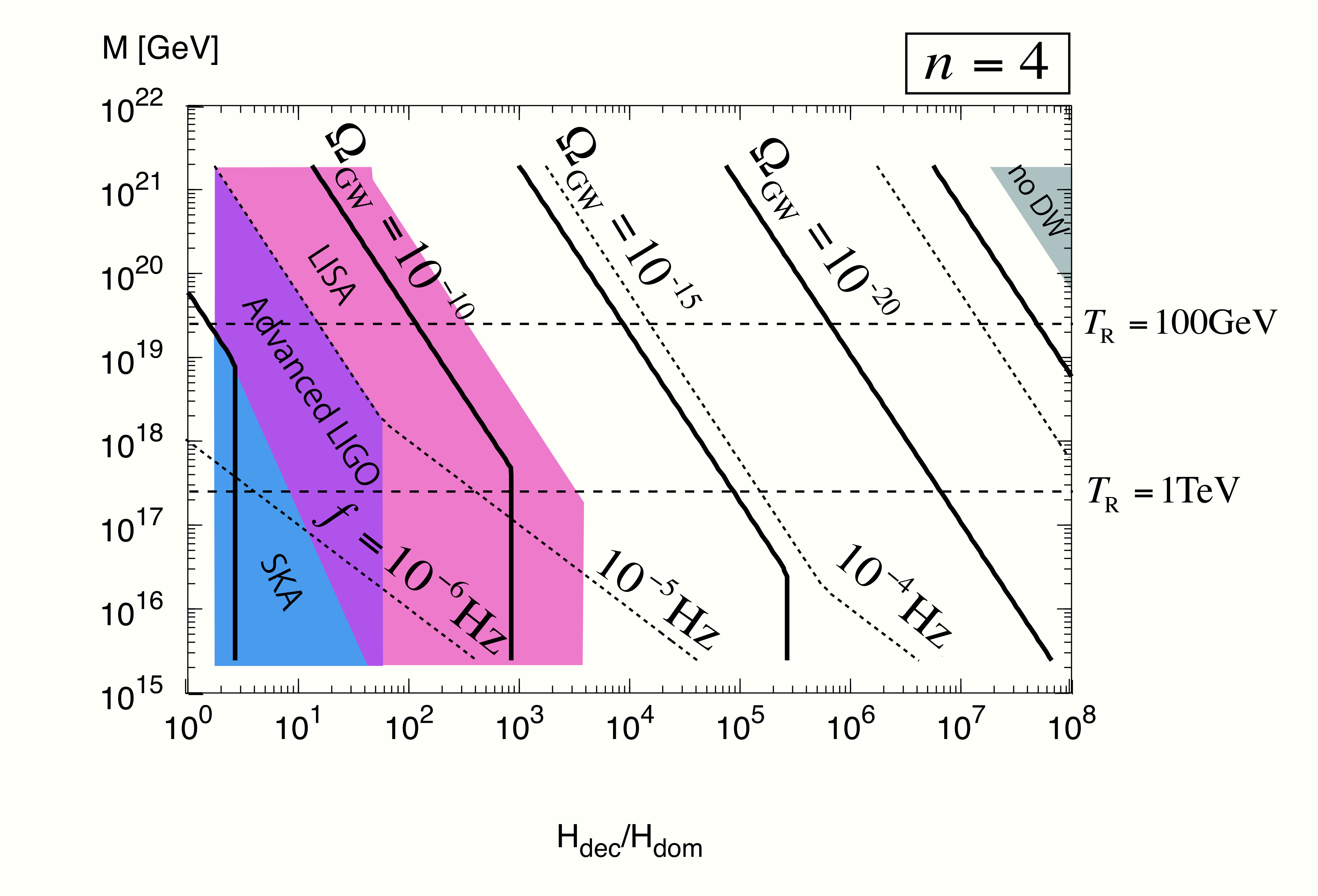
T.Moroi and KN, 1105.6216

$W = k\phi Q\bar{Q}$ (Needed for thermal mass for flaton)

$\longrightarrow$ Bias $V_\epsilon \sim \Lambda_{\rm QCD}^4$

$\longrightarrow$ DWs decay at $T \sim \Lambda_{\rm QCD}$

GWs from DWs



T.Moroi and KN, 1105.6216

Baryogenesis

- Baryogenesis through Affleck-Dine after TI
- Flaton affects the Higgs dynamics $W = \frac{\phi^2}{M} H_u H_d$
- Higgs affects the slepton dynamics $W = \frac{1}{M} L H_u L H_u$
- Angular motion of LHu direction corresponds to lepton number
- Baryogenesis through Affleck-Dine leptogenesis

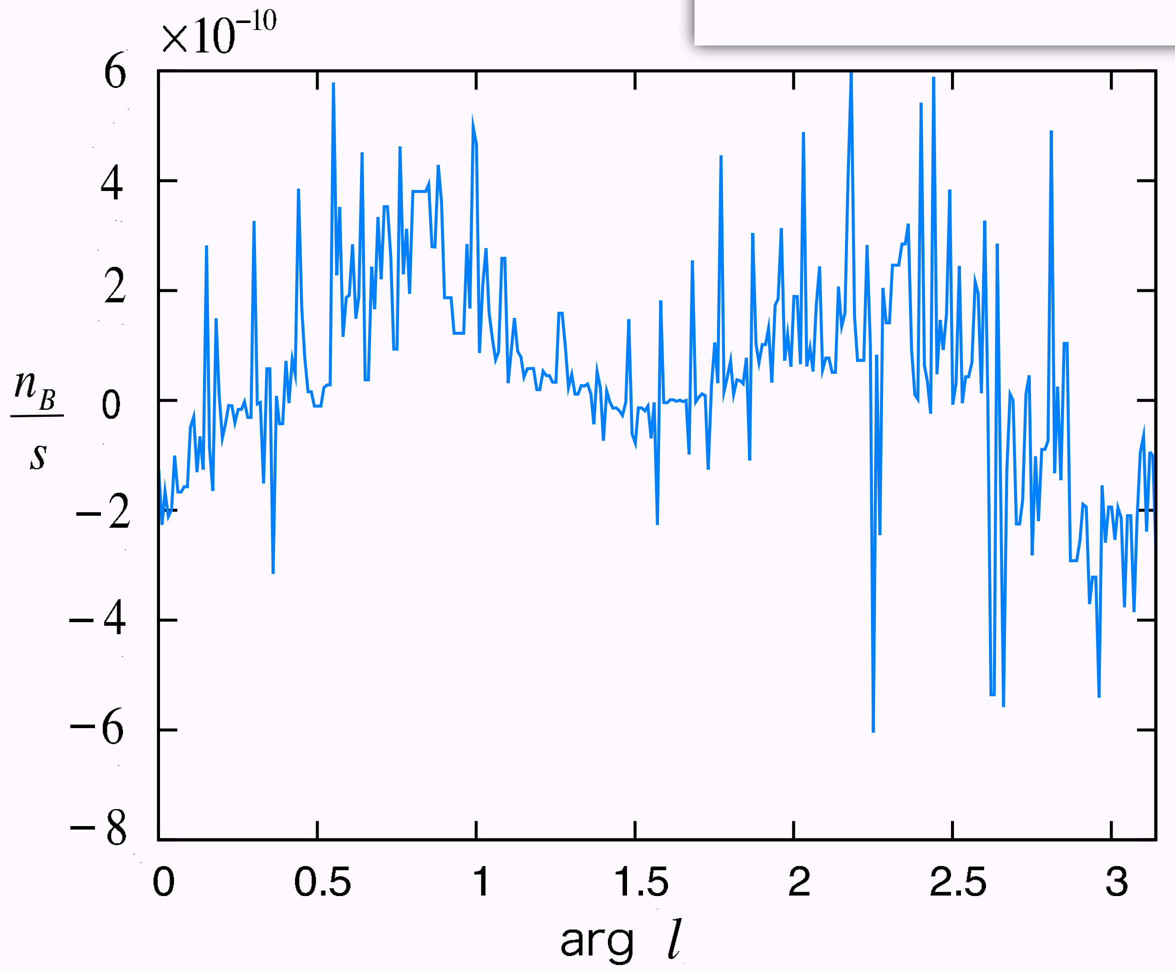
[Stewart, Kawasaki, Yanagida (1996), Kawasaki, KN (2006), Felder et al. (2007), Kim, Park, Stewart (2008)]

Very complicated scalar dynamics

$$\begin{aligned}W =&\, y^u Q H_u u + y^d Q H_d d + y^e L H_d e + \frac{\lambda_\phi}{4M}\phi^4 \\ &+ \frac{\lambda_\nu}{2M_\nu}(LH_u)(LH_u) + \frac{\lambda_\mu}{M}\phi^2 H_u H_d.\end{aligned}$$

$$\begin{aligned}V_F =&\, \frac{1}{M^2}\Big\{|\lambda_\phi\phi^3 + 2\lambda_\mu\phi h_u h_d|^2 + |\lambda_\nu l h_u^2|^2 \\ &+ |\lambda_\mu\phi^2 h_d + \lambda_\nu l^2 h_u|^2 + |\lambda_\mu\phi^2 h_u|^2\Big\}.\end{aligned}$$

$$\begin{aligned}V_{\rm SB} =&\, V_0 - m_\phi^2|\phi|^2 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 \\ &+ \Big\{\frac{A_\phi\lambda_\phi}{4M}\phi^4 + \frac{A_\mu\lambda_\mu}{M}\phi^2 h_u h_d + \frac{A_\nu\lambda_\nu}{2M} l^2 h_u^2 + \text{c.c.}\Big\}\end{aligned}$$



[Kawasaki, KN (2006)]

What's flaton?

- It gives mu-term (Higgsino mass) through Kim-Nilles

$$W = \frac{\phi^2}{M} H_u H_d \longrightarrow \quad \mu = \frac{\langle\phi\rangle^2}{M}$$

[Kim, Nilles (1984)]

- Peccei-Quinn scalar can take role of flaton

[Chun, Comelli, Lyth (1999), Kim, Park, Stewart (2008)]

  - $U(1)_{\mathrm{PQ}}$ forbids NR terms like ϕ^n
  - $U(1)_{\mathrm{PQ}}$ is anomalous under QCD

    $\longrightarrow$ Axionic domain wall problem
  - Needs models avoiding DW problem $N_{\mathrm{DW}} = 1$

Summary of thermal inflation

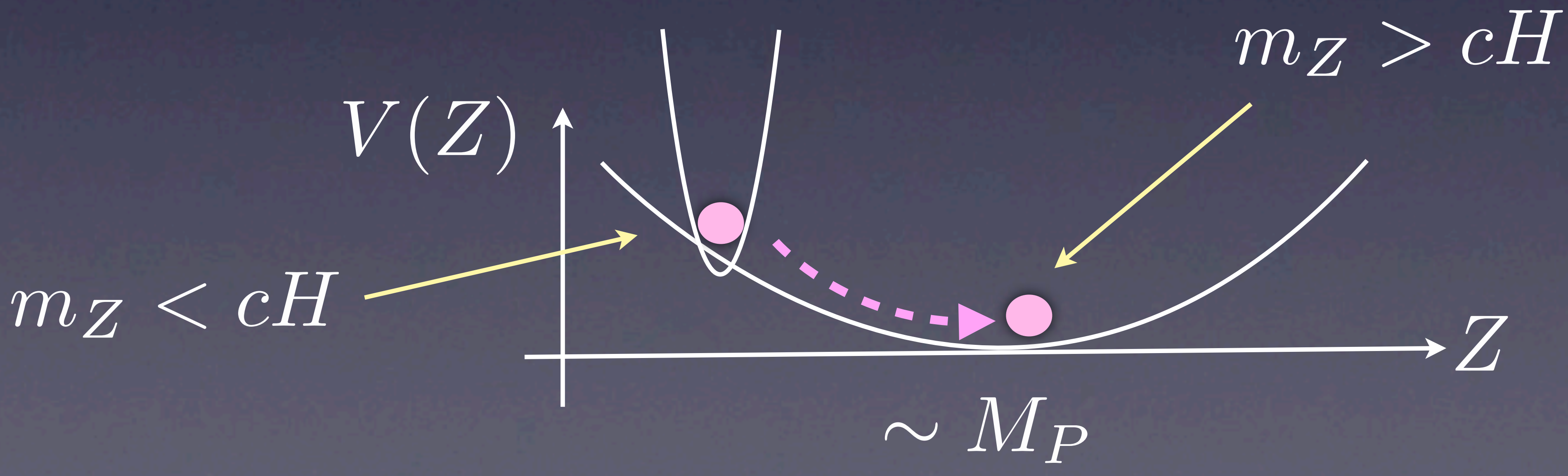
- It is possible to solve the moduli problem.
- Domain walls are necessarily formed. QCD anomaly effect may solve DW problem.
- Baryon asymmetry is also diluted. Baryogenesis after thermal inflation may be possible through modified Affleck-Dine.
- Both mechanisms are possible only for limited parameter ranges. It is still unclear all of them are consistent.

3. Adiabatic Suppression

Adiabatic suppression

- Linde (1996) proposed that moduli oscillation amplitude is exponentially suppressed if it has large Hubble mass term.

$$-\mathcal{L} = m_Z^2 (Z - Z_0)^2 + c^2 H^2 Z^2 \qquad c \gtrsim \mathcal{O}(10)$$



Large Hubble mass?

- Is it natural to have large Hubble mass ?
- Planck-suppressed coupling $\longrightarrow$ $C \sim 1$

$$K \sim \frac{1}{M_P^2}|Z|^2|I|^2 \to -\mathcal{L} \sim H^2|Z|^2 \qquad I : \text{inflaton}$$

- Strong dynamics at Planck scale $\longrightarrow$ $C \sim \mathcal{O}(10)$

[F.Takahashi, T.Yanagida (2010)]

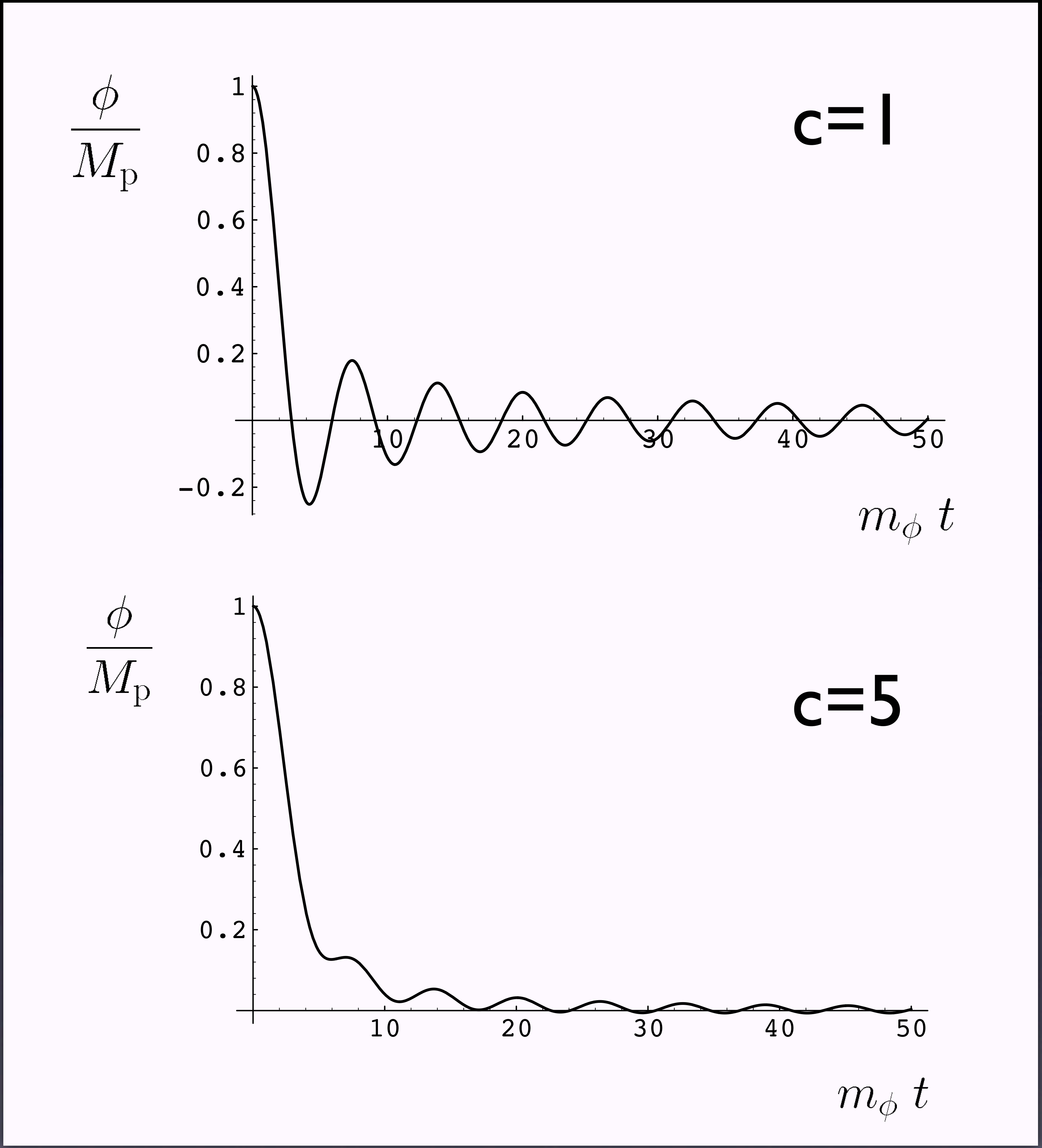
- Enhanced coupling for some reason?

- Moduli amplitude is suppressed for large c
- Suppression factor :

$$\frac{3\sqrt{2p\pi}}{4}C^{\frac{3p+1}{2}}\ \exp\left(-\frac{C\pi p}{2}\right)$$

- $C \gg 10 \longrightarrow$

solve moduli problem without entropy production



[A.D.Linde (1996)]

Adiabaticity

$$-\mathcal{L} = m_Z^2 (Z - Z_0)^2 + c^2 H^2 Z^2 \quad \longrightarrow \quad Z_{\rm min} = \frac{C^2 H^2}{C^2 H^2 + m_Z^2} Z_0$$

- Adiabaticity is violated at

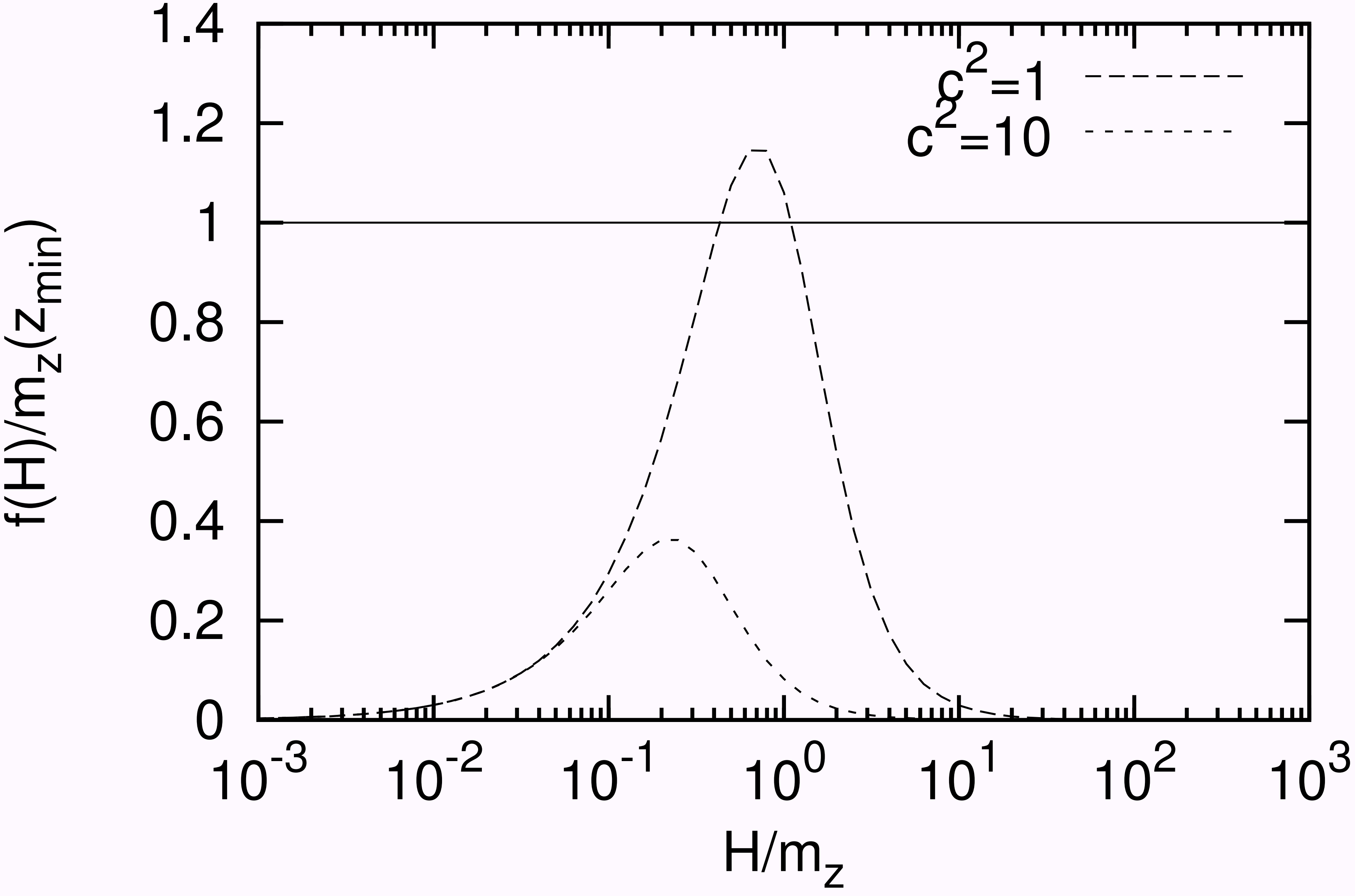
$$\left| \frac{\dot{Z}_{\rm min}}{Z_{\rm min}} \right| > m_Z^{\rm eff} \qquad m_Z^{\rm eff} \equiv \sqrt{m_Z^2 + C^2 H^2}$$

- If $C \sim 1$ adiabaticity is violated at $H \sim m_Z$

  $\longrightarrow$ moduli are produced

- If $C \gg 1$ adiabaticity is never violated except for at the end of inflation

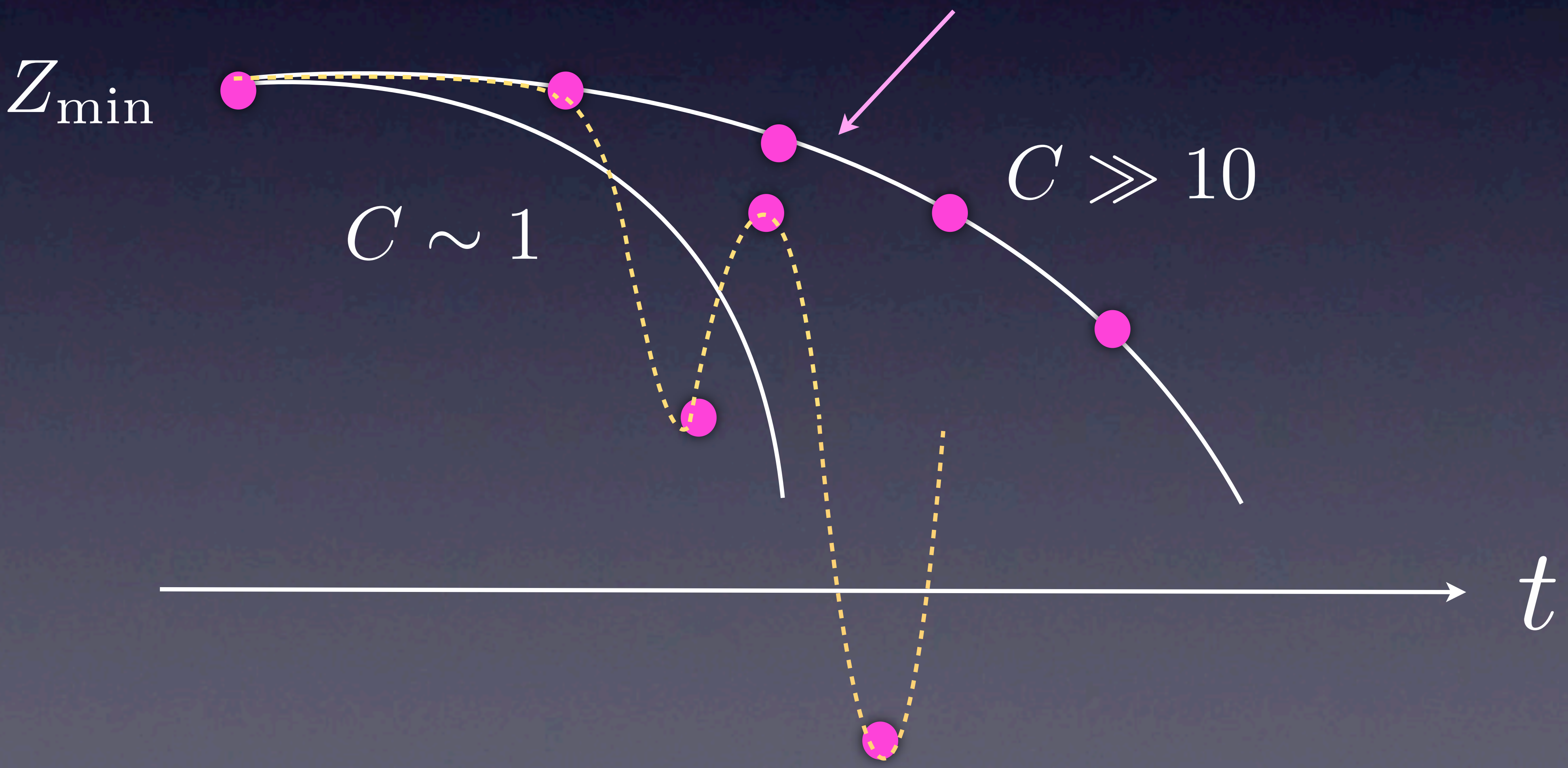
[KN, F.Takahashi, T.Yanagida, in prep.]


1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
H/m_z
$f(H)/m_z(z_{min})$
$c^2=1$
$c^2=10$

- Moduli oscillation at $H \sim m_Z / C$

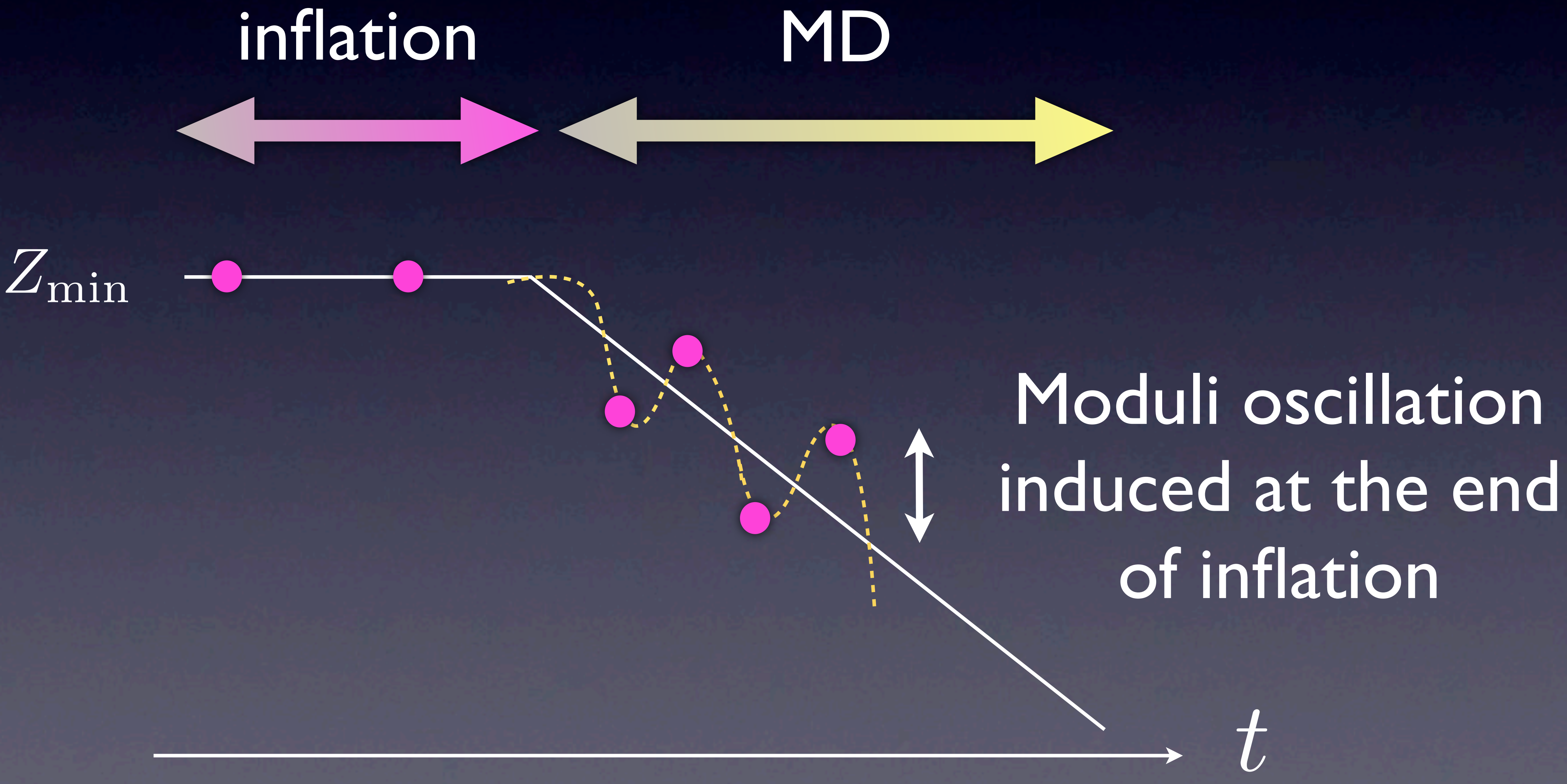
$$Z_{\rm min} = \frac{C^2 H^2}{C^2 H^2 + m_Z^2} Z_0 \qquad \dot{Z}_{\rm min} = - \frac{3 m_Z^2 H}{m_Z^2 + C^2 H^2} Z_0$$

Moduli oscillation is exponentially suppressed for large C



- Moduli oscillation at $H \sim H_{\rm inf}$

$$Z_{\rm min} = \frac{C^2 H^2}{C^2 H^2 + m_Z^2} Z_0 \qquad \dot{Z}_{\rm min} = -\frac{3 m_Z^2 H}{m_Z^2 + C^2 H^2} Z_0$$



inflation

MD

$Z_{\rm min}$

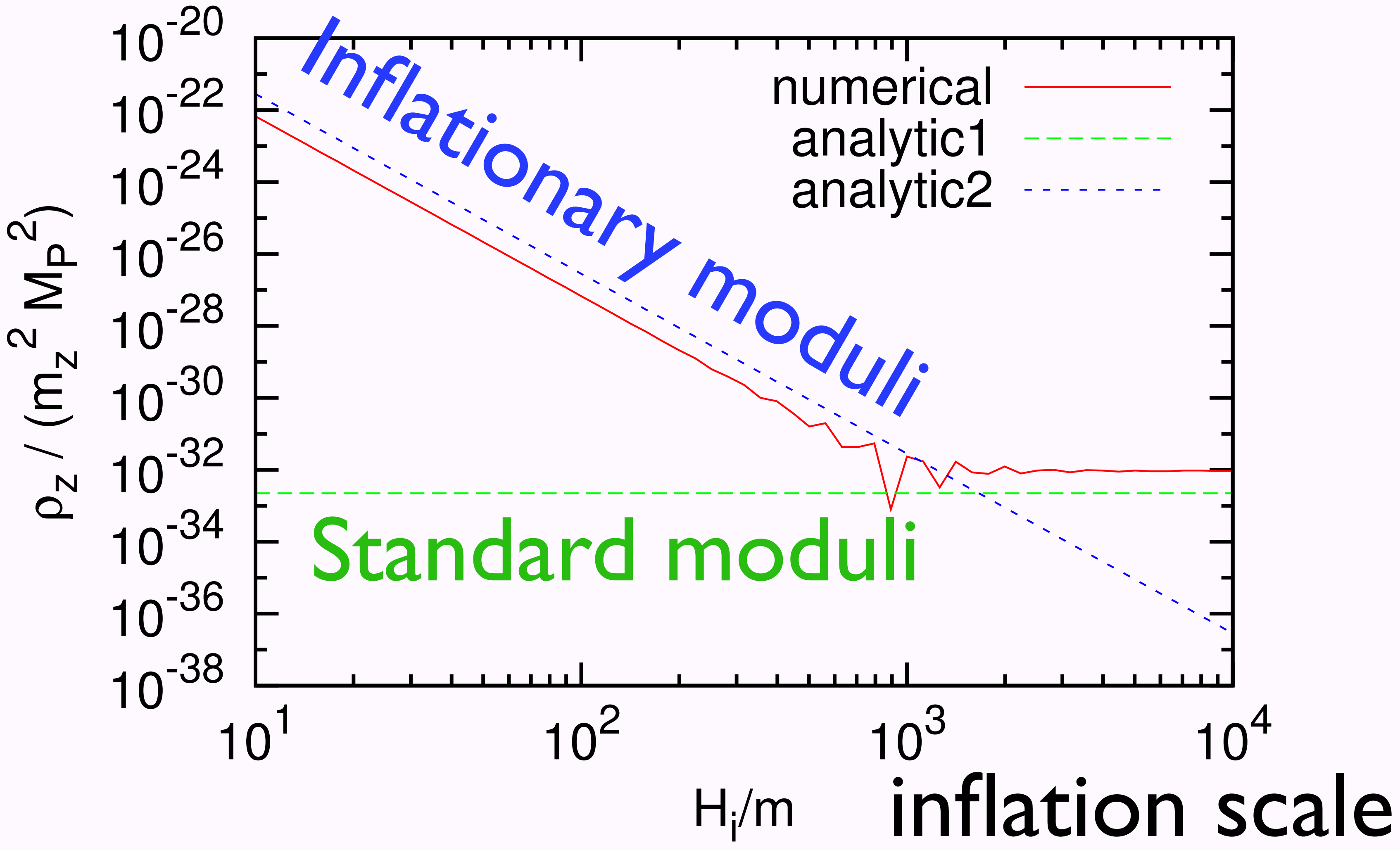
t

Moduli oscillation
induced at the end
of inflation

- The end of inflation involves non-adiabatic process

  Moduli are necessarily produced at inflation end.

Moduli abundance (C=30)



Even in the adiabatic solution, there is model dependent lower bound on the moduli abundance

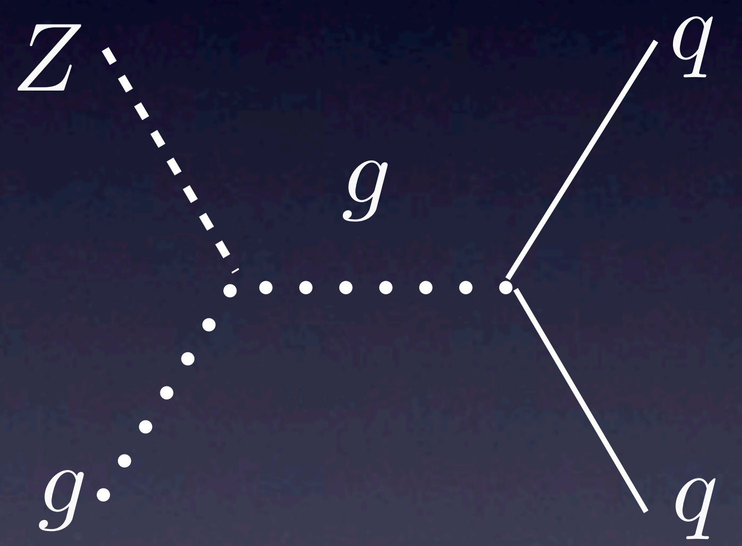
[KN, F.Takahashi, T.Yanagida, in prep.]

Thermal Moduli

- Moduli are also produced scattering of particles in thermal bath, similar to gravitino

$$Y_Z \sim Y_{3/2} \sim 2 \times 10^{-12} \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right)$$

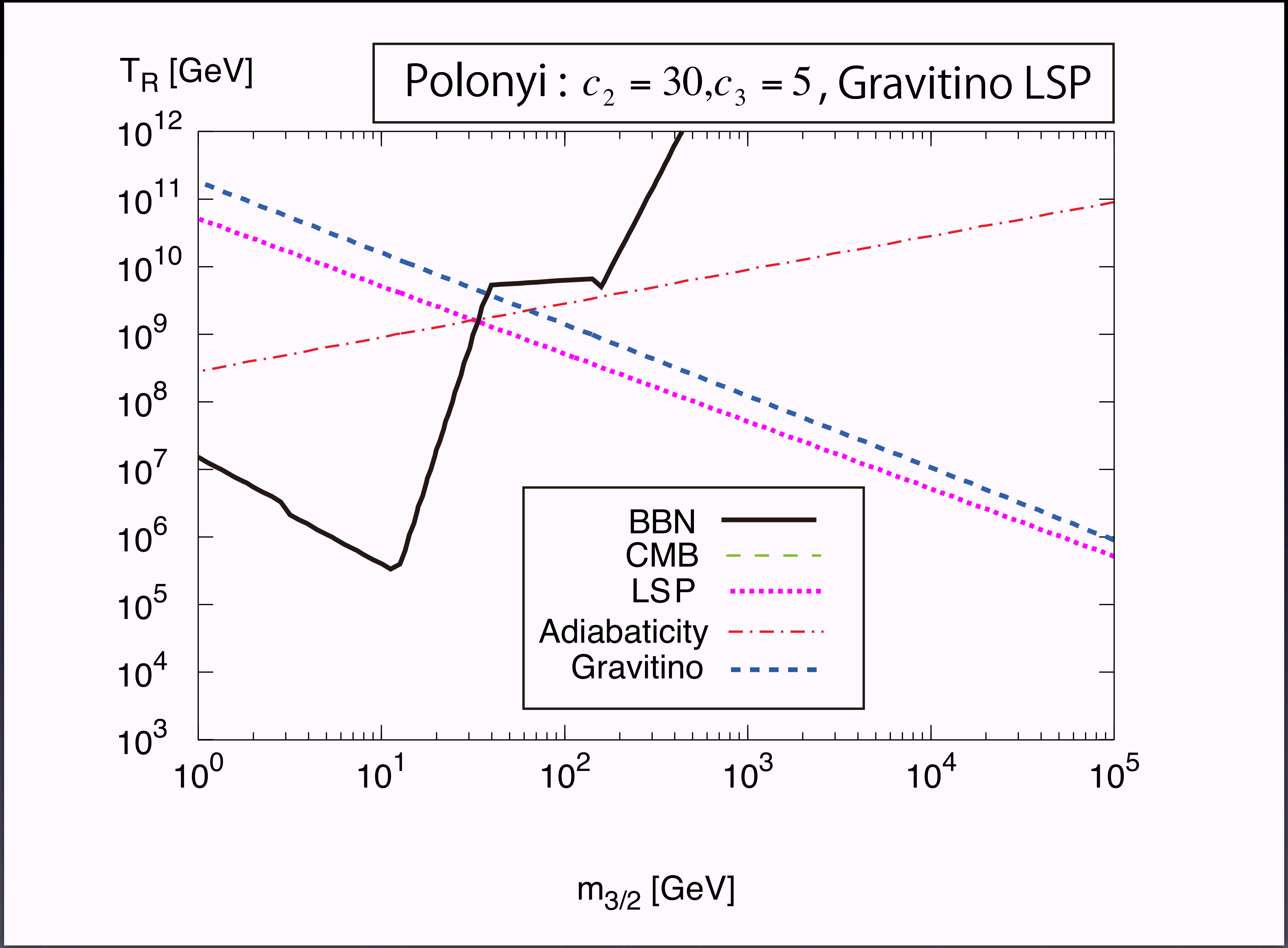
$$\mathcal{L} \sim \int d^2\theta C \frac{Z}{M_P} W_a W^a \qquad Y \equiv \frac{n}{s}$$



- If moduli also couple to SM sector strongly, the abundance is enhanced by the factor $\sim C^2$

- If so, the moduli lifetime becomes shorter by $\sim C^2$

Constraint on reheating temperature in adiabatic suppression scenario



[KN, F.Takahashi, T.Yanagida, in prep.]

Summary of adiabatic suppression

- If moduli obtain large Hubble mass, the moduli amplitude is significantly suppressed.
- However, moduli oscillation is induced at the end of inflation. Only Single-field inflation is allowed.
- Moduli are also produced from thermal scatter.
- Still there is stringent upper bound on reheating.
- There is no need for entropy production.

Summary

- Polonyi/Moduli controls the visible sector.
- Moduli cosmology : highly non-trivial and important.
- A way to probe/constrain string theory.
- Let’s discuss !