On the adiabatic solution to the moduli problem

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Workshop @ Toyama Univ (2012/2/21)

KN, F.Takahashi, T.T.Yanagida arXiv:1109.2073

KN, F.Takahashi, T.T.Yanagida arXiv:1112.0418

M.Kawasaki, N.Kitajima, KN, arXiv:1112.2818

Contents

- Cosmological Polonyi/Moduli Problem
- Adiabatic solution to the Polonyi/moduli problem
- Relation to the 125GeV Higgs

Polonyi field

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

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

- Giving SUSY particle masses through

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

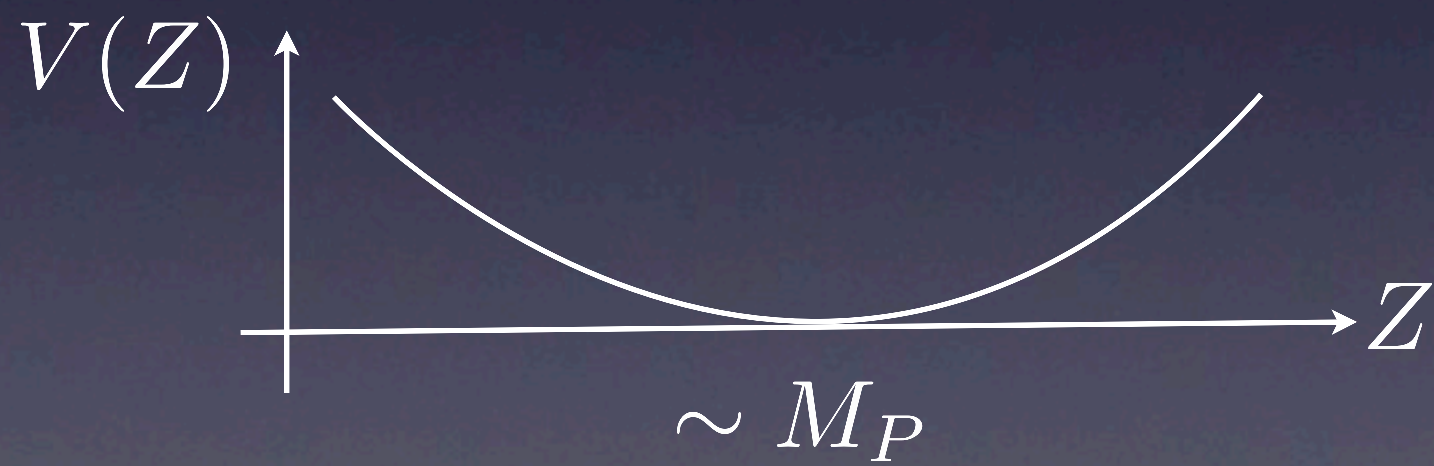
$$\mathcal{L} \sim \int d^4\theta \frac{Z^\dagger Z}{M_P^2} |f|^2 \sim m_{\tilde{f}}^2 |\tilde{f}|^2 \qquad m_{\tilde{g}} \sim m_{\tilde{f}} \sim \frac{F_Z}{M_P}$$

Polonyi potential

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

  Kahler potential $K = |Z|^2$

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



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

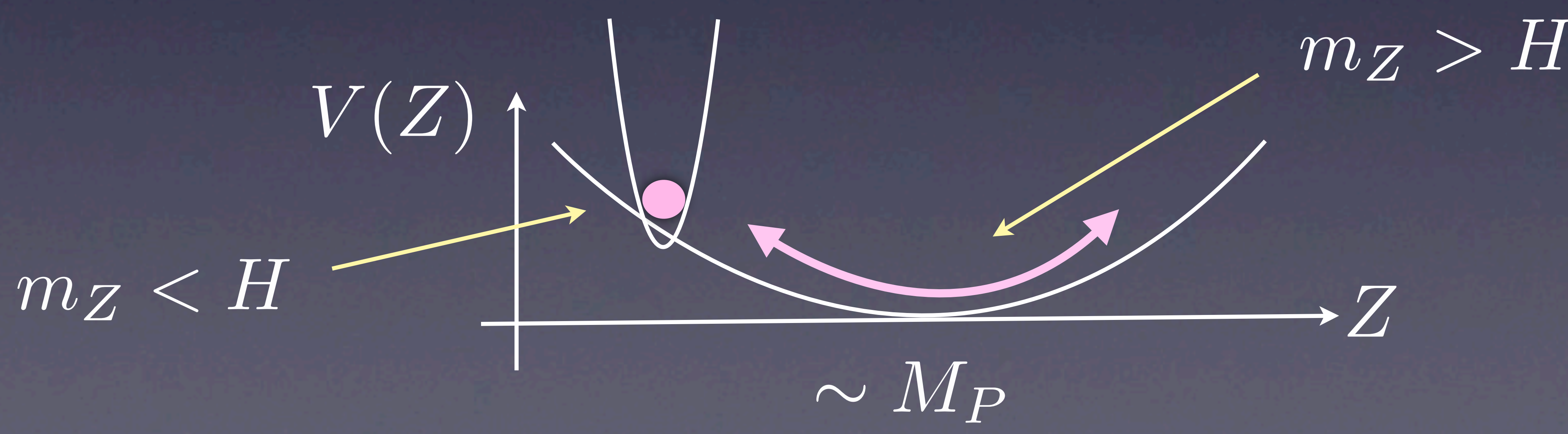
Polonyi Problem

- Polonyi has Hubble mass during/after inflation

$$K \sim \frac{1}{M_P^2}|Z|^2|I|^2 \to -\mathcal{L} \sim H^2|Z|^2 \qquad |F_I|^2 = V_I \sim H^2 M_P^2$$

I : 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

[Kawasaki, Kohri, Moroi, 2005]

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

20 orders of magnitude tuning ?

Polonyi Problem

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Hierarchy Problem !

- Big bang nucleosynthesis constraint

[Kawasaki, Kohri, Moroi, 2005]

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

20 orders of magnitude tuning ?

Moduli Problem

- Moduli : light scalar appearing after compactification of extra dim. in string theory
- 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)]

Solutions

- Moduli is heavy enough to decay before BBN

  $\longrightarrow$ Moduli-induced gravitino problem

  [Endo, Hamaguchi, Takahashi (06), Nakamura, Yamaguchi (06)]

  $\longrightarrow$ Dilution of the baryon asymmetry

- Thermal inflation to dilute the moduli

  $\longrightarrow$ Domain wall problem

  [See, however, T.Moroi, KN, 1105. 6216]

  $\longrightarrow$ Dilution of the baryon asymmetry

- Adiabatic suppression mechanism

Adiabatic Suppression

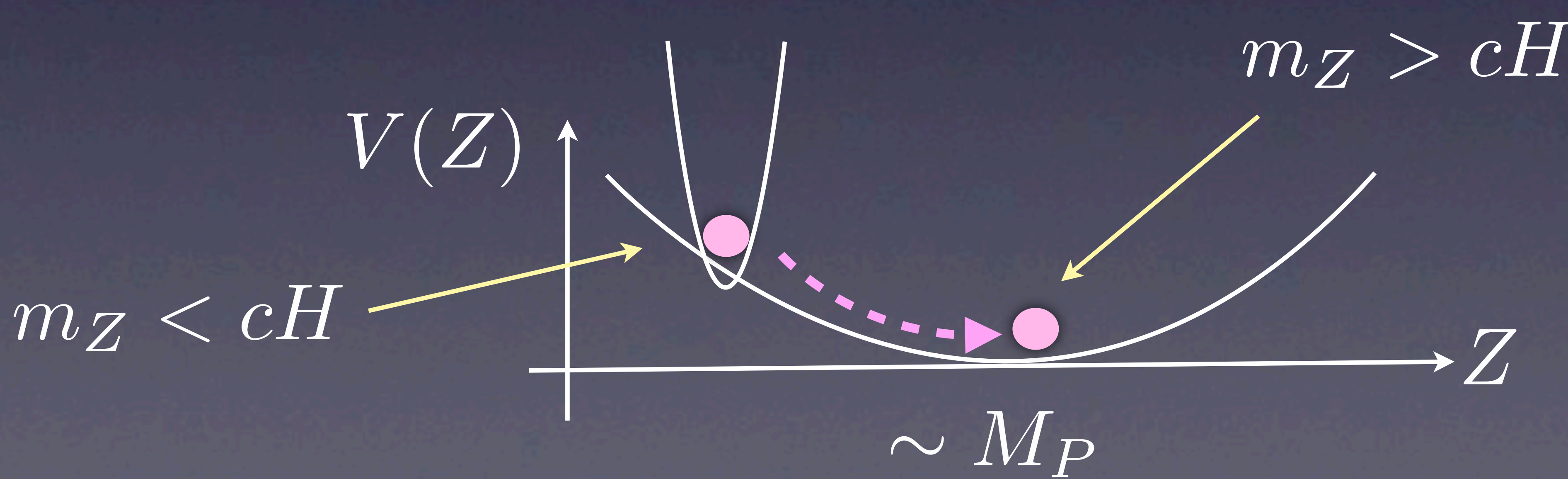
KN, F.Takahashi, T.T.Yanagida arXiv:1109.2073

KN, F.Takahashi, T.T.Yanagida arXiv:1112.0418

Adiabatic suppression

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

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

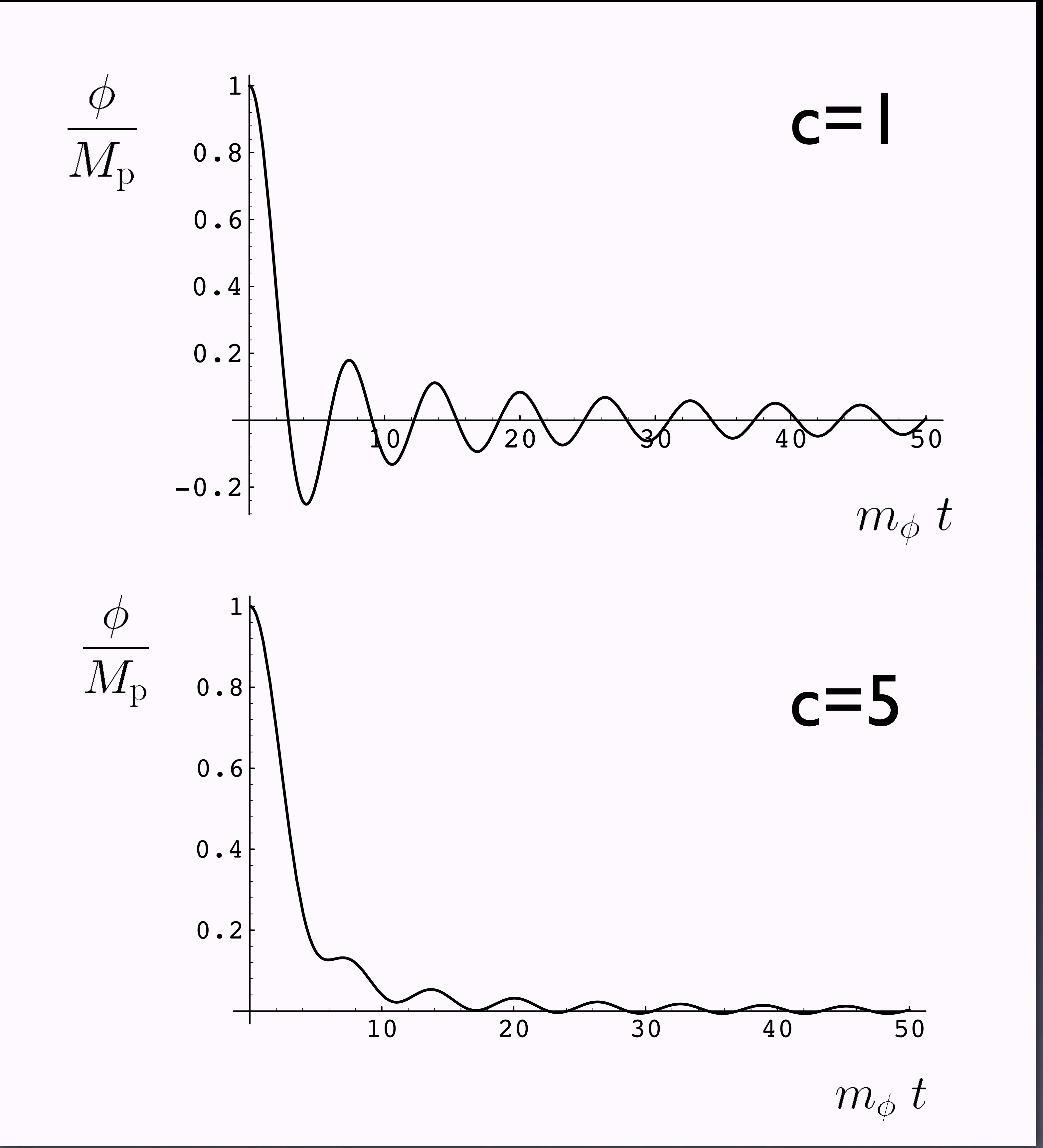


- Moduli amplitude is suppressed for large c
- Suppression factor :

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

- $C \gg 10 \longrightarrow$

solve moduli problem without entropy production



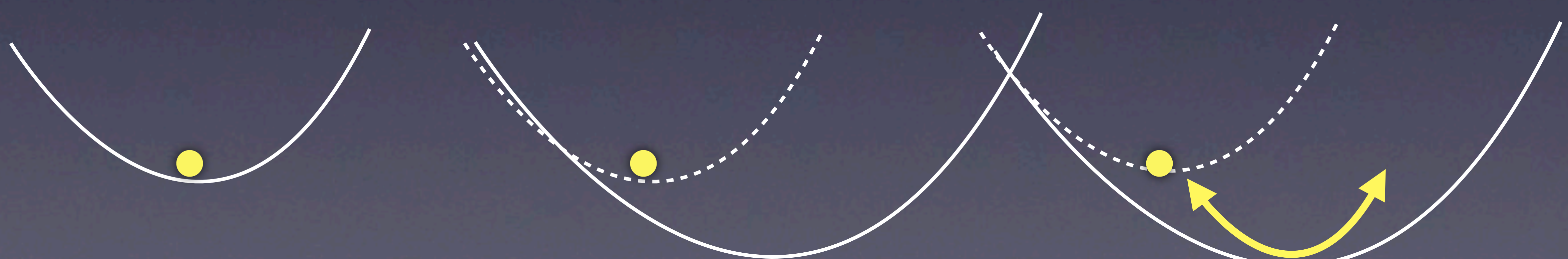
[A.D.Linde (1996)]

Schematic picture

- Potential changes adiabatically : $m_z \gg |\dot{z}_{\rm min}/z_{\rm min}|$

No oscillation

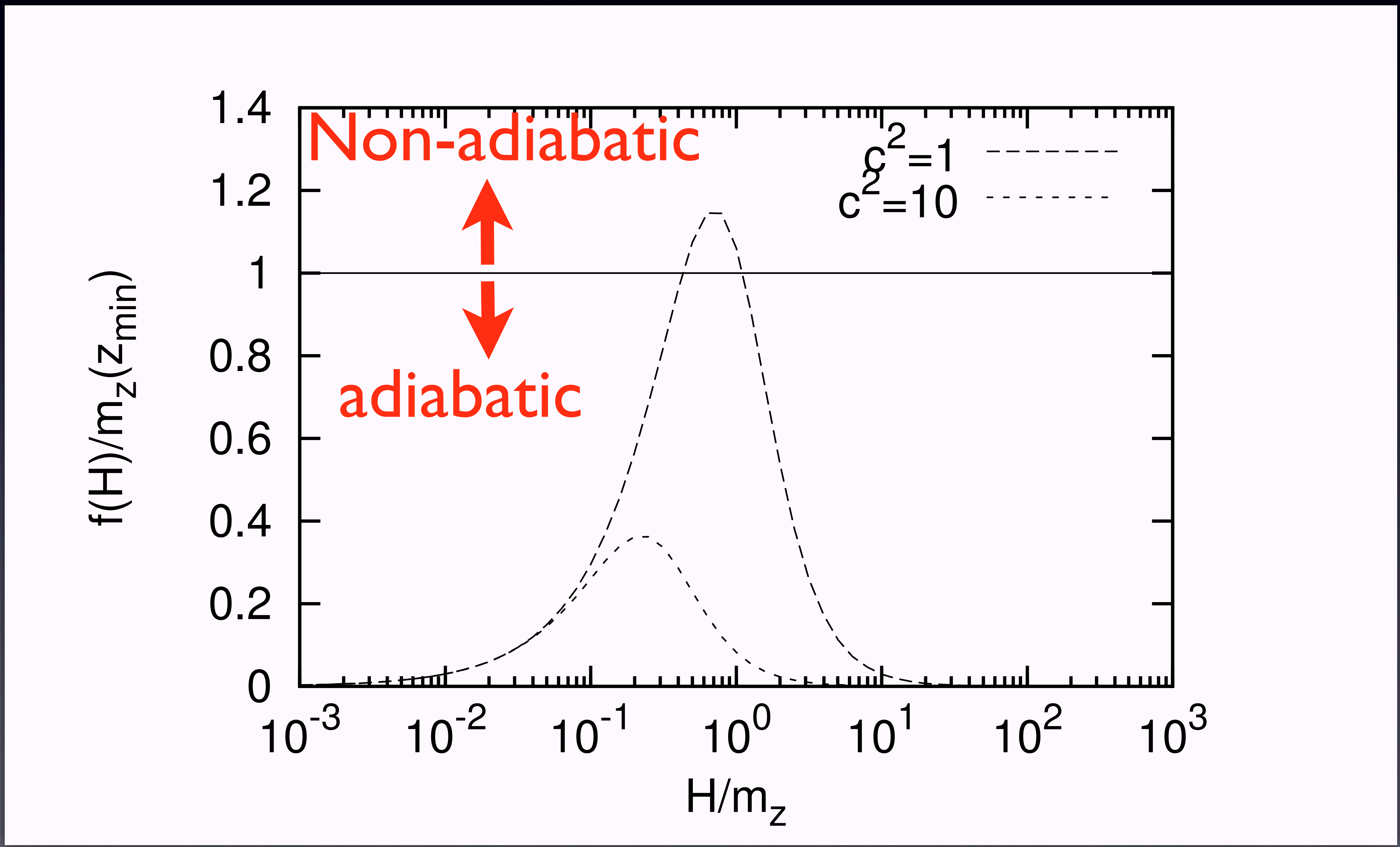
- Potential changes non-adiabatically : $m_z \ll |\dot{z}_{\rm min}/z_{\rm min}|$



Oscillation is induced

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

$$f(H) = \dot{z}_{\rm min} / z_{\rm min}$$



Moduli production at the end of inflation

- The moduli dynamics is adiabatic as long as there is no timescale faster than the moduli mass
- The Hubble parameter changes adiabatically in M.D. or R.D. era $m_z^{(\mathrm{eff})} \sim cH$ $\dot{H} \sim H^2$
- Is this true for whole the history? No!
- The Hubble parameter changes at the end of inflation with timescale of inflaton mass m_ϕ

$\dot{H} \sim m_\phi H$ Adiabaticity is violated if $m_\phi \gg H_{\mathrm{inf}}$

[KN, F.Takahashi, T.Yanagida, 2011]

Moduli abundance

- SUGRA single-field inflation case

$$K = |Z|^2 + |\phi|^2 + c^2 \frac{|\phi|^2 |Z - Z_*|^2}{M_P^2}$$

ϕ : inflaton

$c \gg 1$

$$\longrightarrow \quad V = \frac{V(\phi)}{M_P^2} |z|^2 + c^2 H^2 |z - z_*|^2$$

$$H^2 = \frac{|\dot{\phi}|^2 + V(\phi)}{3M_P^2}$$

During inflation : $V(\phi)/M_P^2 = 3H^2 \longrightarrow z_{\rm min} = \dfrac{c^2 z_*}{c^2 + 3}$

After inflation : $\langle V(\phi)/M_P^2 \rangle = 3H^2/2 \longrightarrow z_{\rm min} = \dfrac{c^2 z_*}{c^2 + 3/2}$

$$\longrightarrow \boxed{\delta z \simeq \frac{3 z_*}{2c^2}}$$

This shift is non-adiabatic if

$$m_\phi \gg m_z = c H_{\rm inf}$$

Moduli abundance

$$\frac{\rho_z}{s} = \frac{m_z \times cH_{\rm inf}(\delta z)^2/2}{3H_{\rm inf}^2 M_P^2}\frac{3T_R}{4} = \frac{9}{32}T_R\left(\frac{z_*}{M_P}\right)^2\left(\frac{m_z}{c^3 H_{\rm inf}}\right)$$

KN, F.Takahashi, T.T.Yanagida, 1109.2073

This amount is always induced at the end of inflation.

(compare it with standard result $\frac{\rho_z}{s} = \frac{1}{8}T_R\left(\frac{z_*}{M_P}\right)^2$)

- This is power suppressed by c (not exponential)
- Suppressed by inflation scale

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

Moduli abundance

- Multi-field inflation case

$$W = Xf(\phi) \qquad K = c_\phi^2 \frac{|\phi|^2|Z - Z_\phi|^2}{M_P^2} + c_X^2 \frac{|X|^2|Z - Z_X|^2}{M_P^2}$$

- Hybrid inflation $\quad W = \kappa X(\phi\bar{\phi} - M^2)$
- Multi-new inflation $\quad W = \kappa X(\phi^n/M^{n-2} - v^2)$

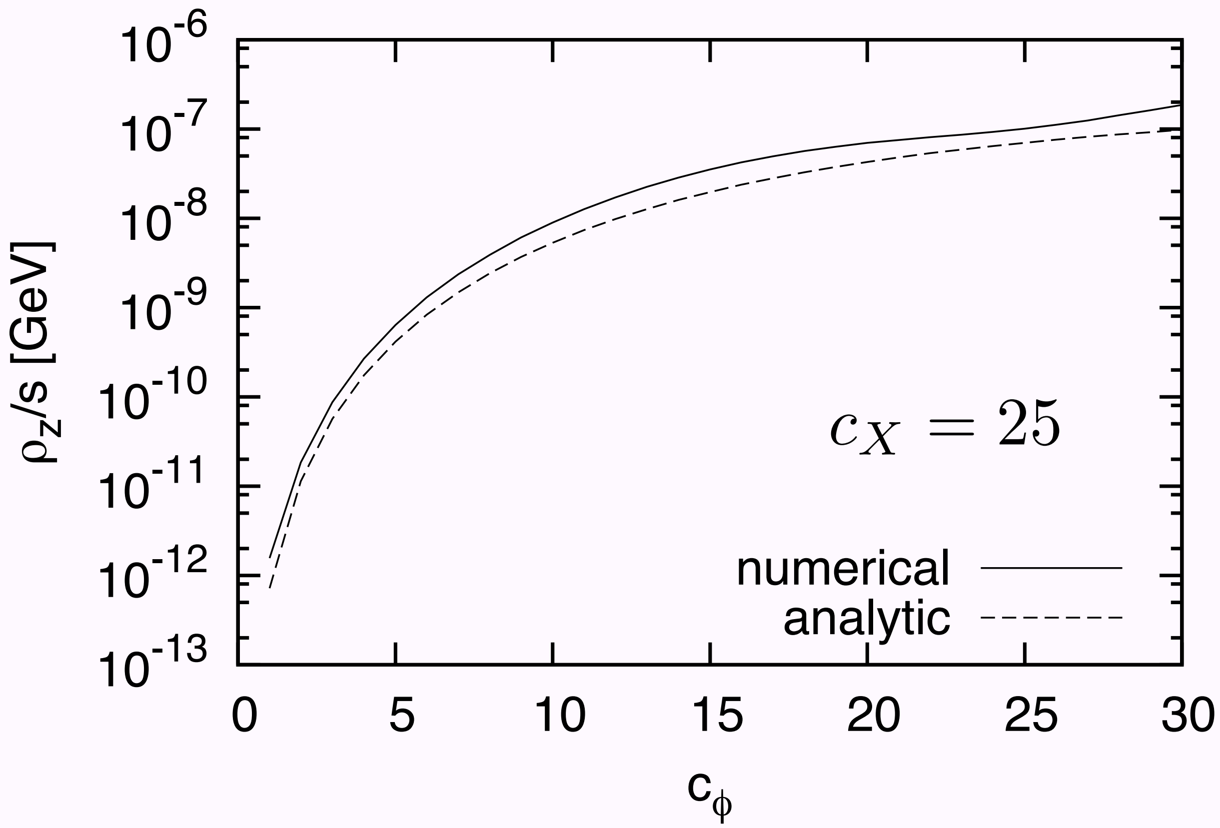
$$V \sim \left(|\dot{\phi}|^2 + |F_\phi|^2\right)\frac{c_\phi^2|z - z_\phi|^2}{M_P^2} + \left(|\dot{X}|^2 + |F_X|^2\right)\frac{c_X^2|z - z_X|^2}{M_P^2}$$

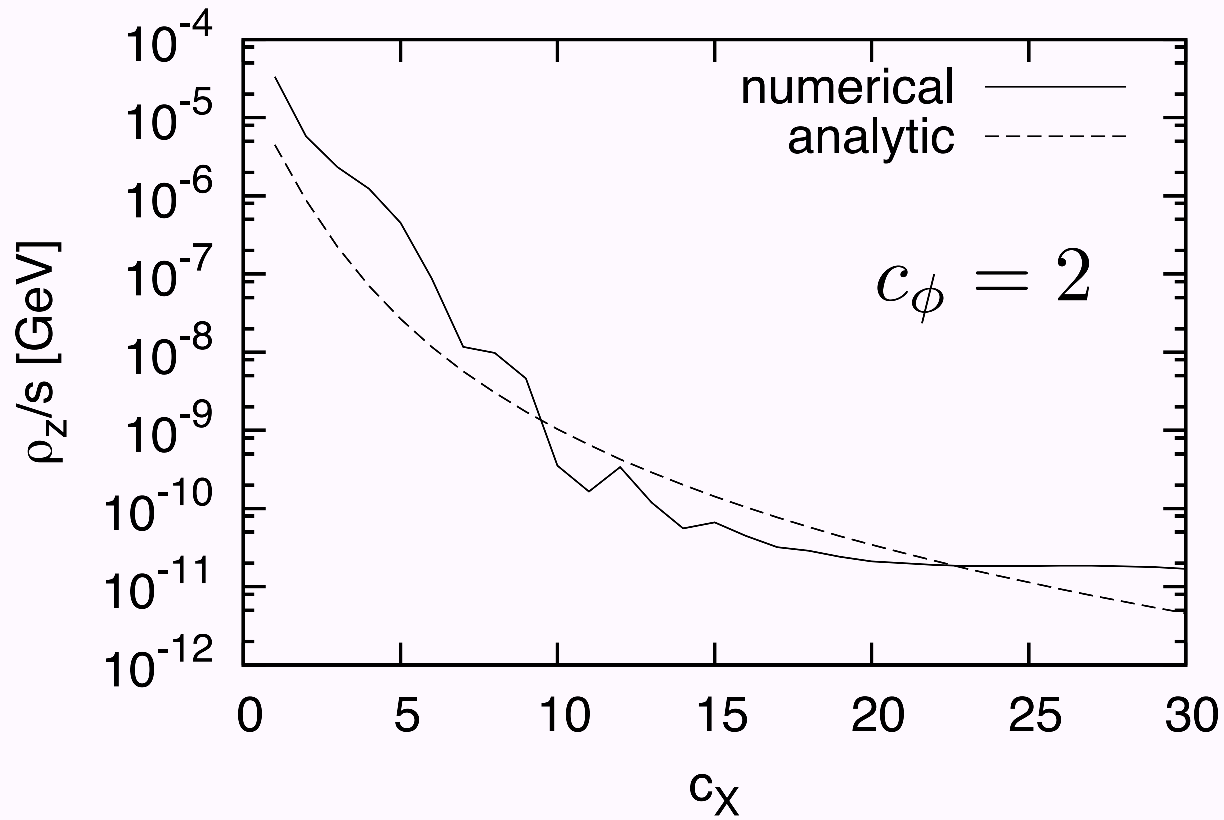
Result : $\boxed{\dfrac{\rho_z}{s} = \dfrac{1}{8}T_R\left(\dfrac{z_X - z_\phi}{M_P}\right)^2\left(\dfrac{c_\phi^4 m_z}{c_X^3 H_{\rm inf}}\right)}$

Results for hybrid inflation

$$z_X = M_P/c_X,\ z_\phi = z_X/2 \qquad m_z = 2\times 10^{-3} M_P$$

$$\Gamma_\phi = 10^{-2.5} M_P \qquad \kappa = 1,\ M = 0.1 M_P$$



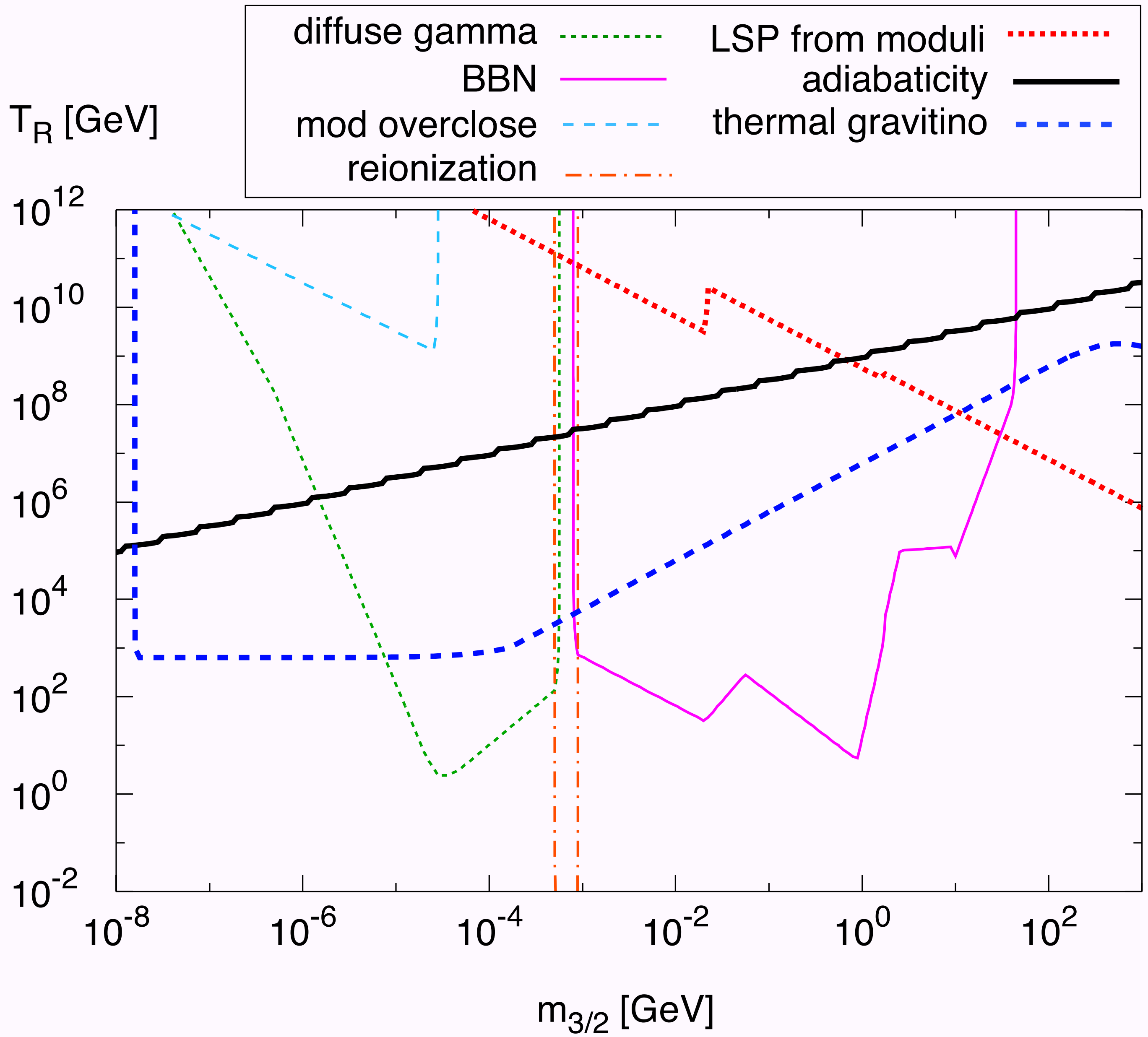


The formula fits with numerical result

Lowcut off theory

KN, F.Takahashi, T.T.Yanagida, 1112.0418

Suppose that moduli interaction strength with c/M_P



No moduli problem for low TR !

$$c = 100$$

$$m_z = c m_{3/2}$$

$$H_{\rm inf} = 10^{13}\,{\rm GeV}$$

$$\Gamma_z \sim \frac{c^2}{8\pi}\frac{m_z^3}{M_P^2}$$

Another example

[M.Kawasaki, N.Kitajima, KN, 1112.2818]

- Another toy model for the adiabatic suppression

$$V = \frac{1}{2}m_\phi^2(\phi-\phi_0)^2 + \frac{1}{2}m_S^2 S^2 + \frac{1}{2}\lambda^2 S^2\phi^2 \qquad m_S, S_i \gg m_\phi$$

- Exercise : evaluate the abundance of ϕ

$$\lambda S \gg m_\phi : \phi \sim 0 \qquad \lambda S \ll m_\phi : \phi \sim \phi_0$$

ϕ oscillates at $\lambda S \sim m_\phi \longleftrightarrow H \sim m_S m_\phi/(\lambda S_i)$

$$\longrightarrow \quad \frac{\rho_\phi}{s} \sim \frac{m_\phi^2\phi_0^2/2}{3H_{\rm os}^2 M_P^2}\frac{3T_R}{4} \sim \frac{T_R}{8}\left(\frac{\lambda S_i}{m_S}\right)^2\left(\frac{\phi_0}{M_P}\right)^2$$

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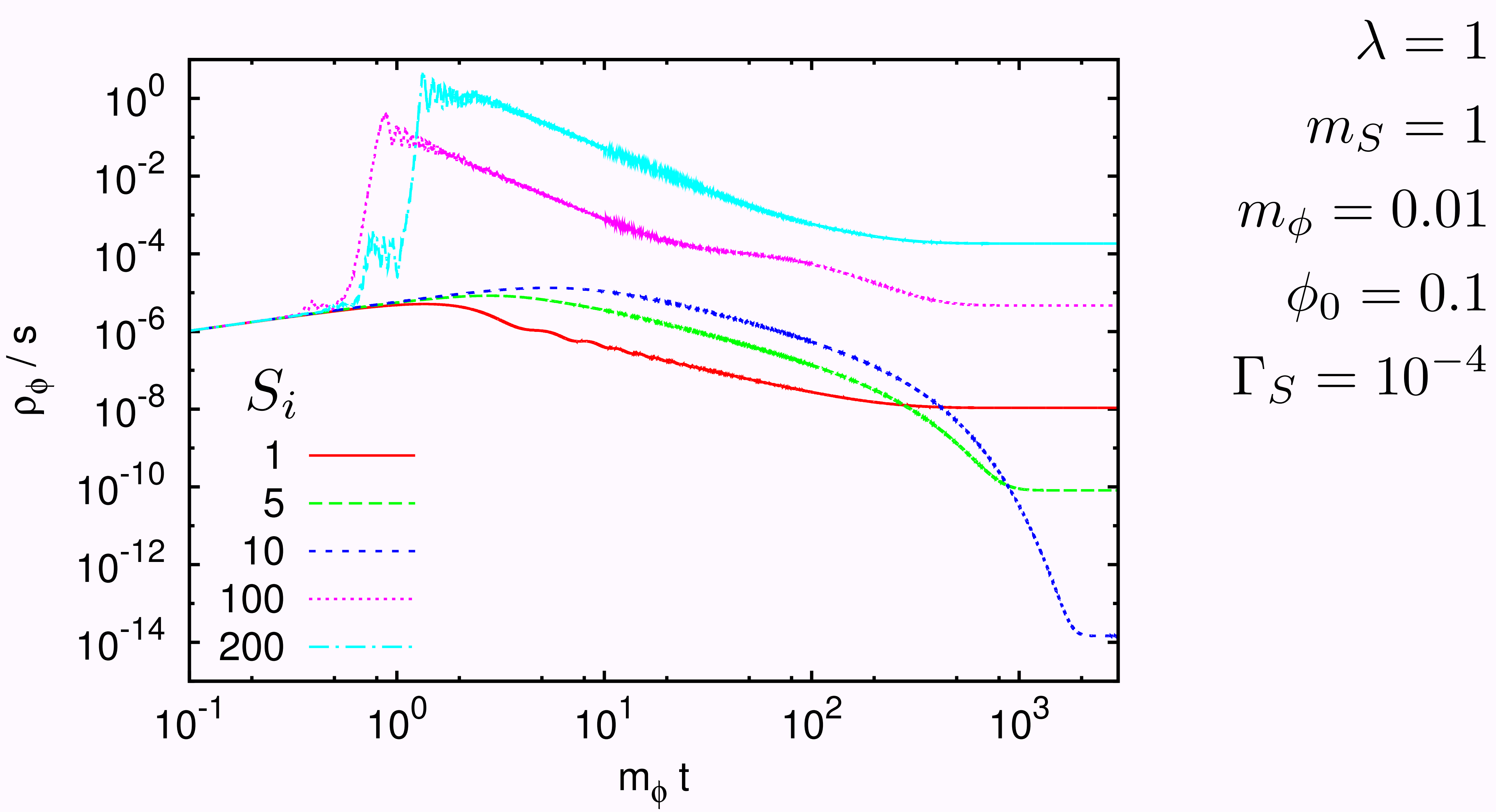
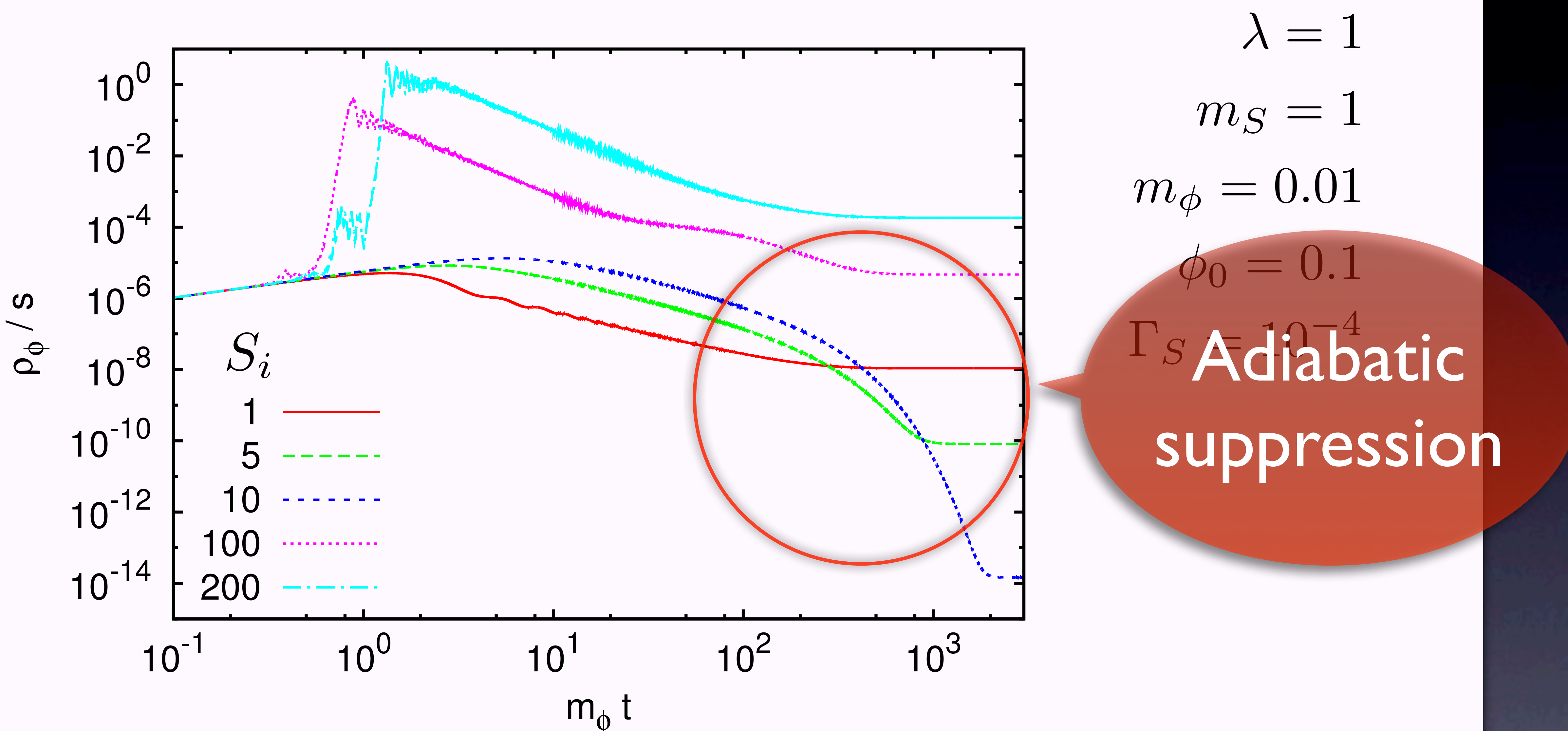
The final abundance of Φ



M.Kawasaki, N.Kitajima, KN, 1112.2818

Many orders of magnitude difference may result unless these effects are carefully taken into account.

The final abundance of Φ



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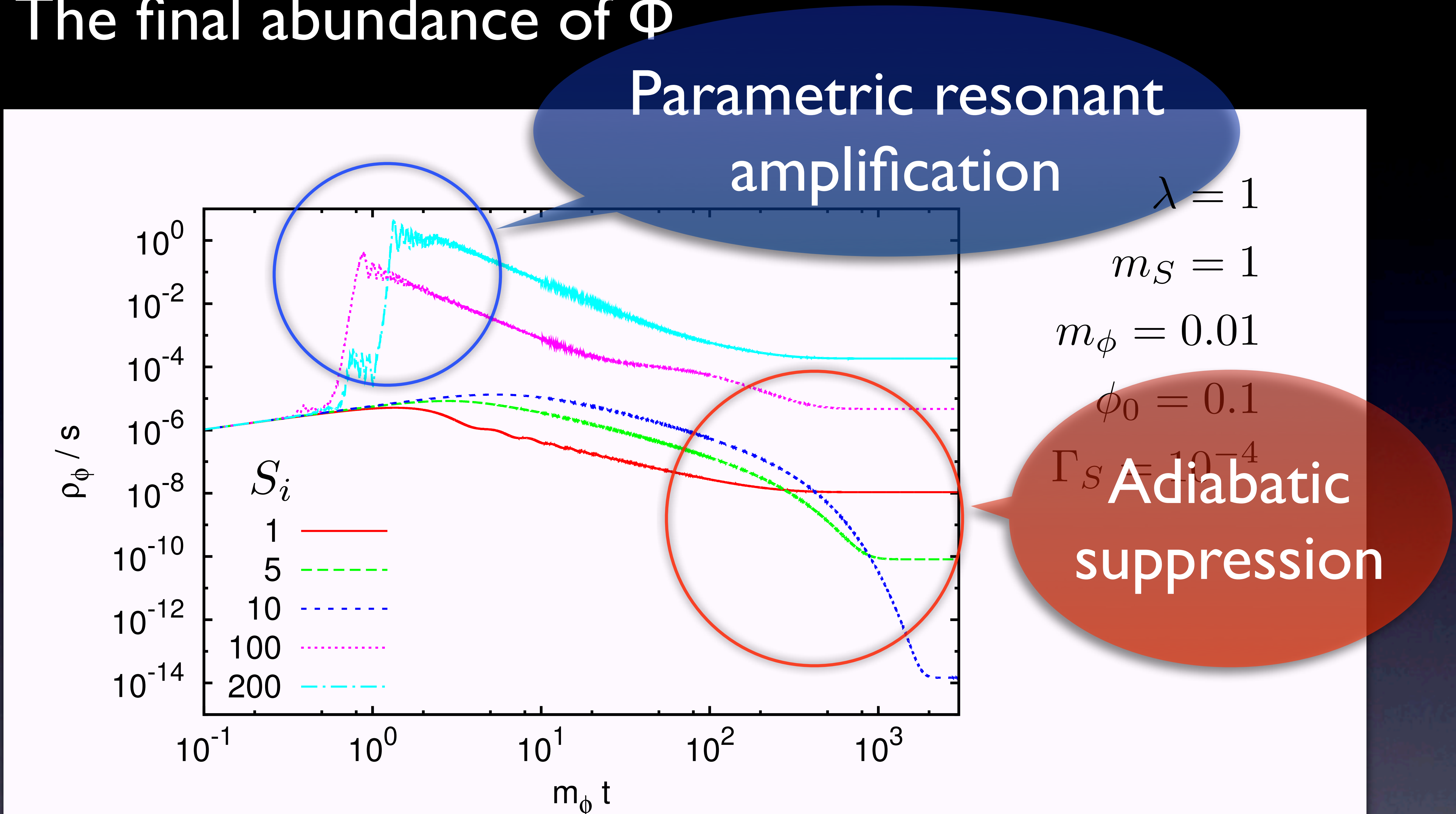

M.Kawasaki, N.Kitajima, KN, 1112.2818

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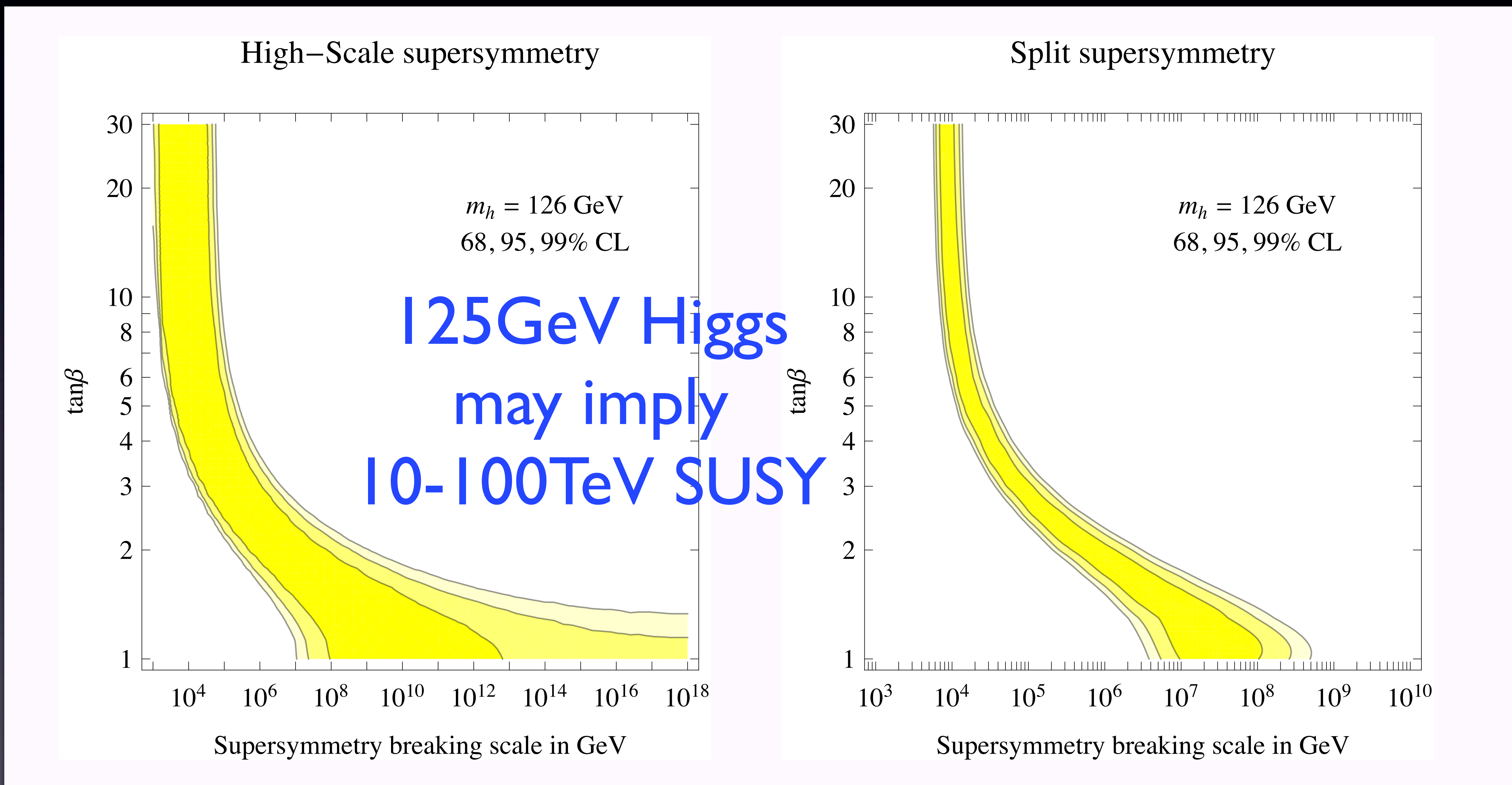
Implications for 125GeV Higgs

High-scale SUSY?



Giudice, Strumia , 1108.6077

Revive Polonyi Model

- O(100)TeV SUSY

  → Anomaly mediation for the gaugino mass

  No Polonyi field

  Ibe, Yanagida 1112.2462 ; Moroi, KN, 1112.3123 ; Ibe, Matsumoto, Yanagida, 1202.2253

- O(10)TeV SUSY J.L.Feng, K.T.Matchev, D.Sanford, 1112.3021

  → Polonyi field for the gaugino mass

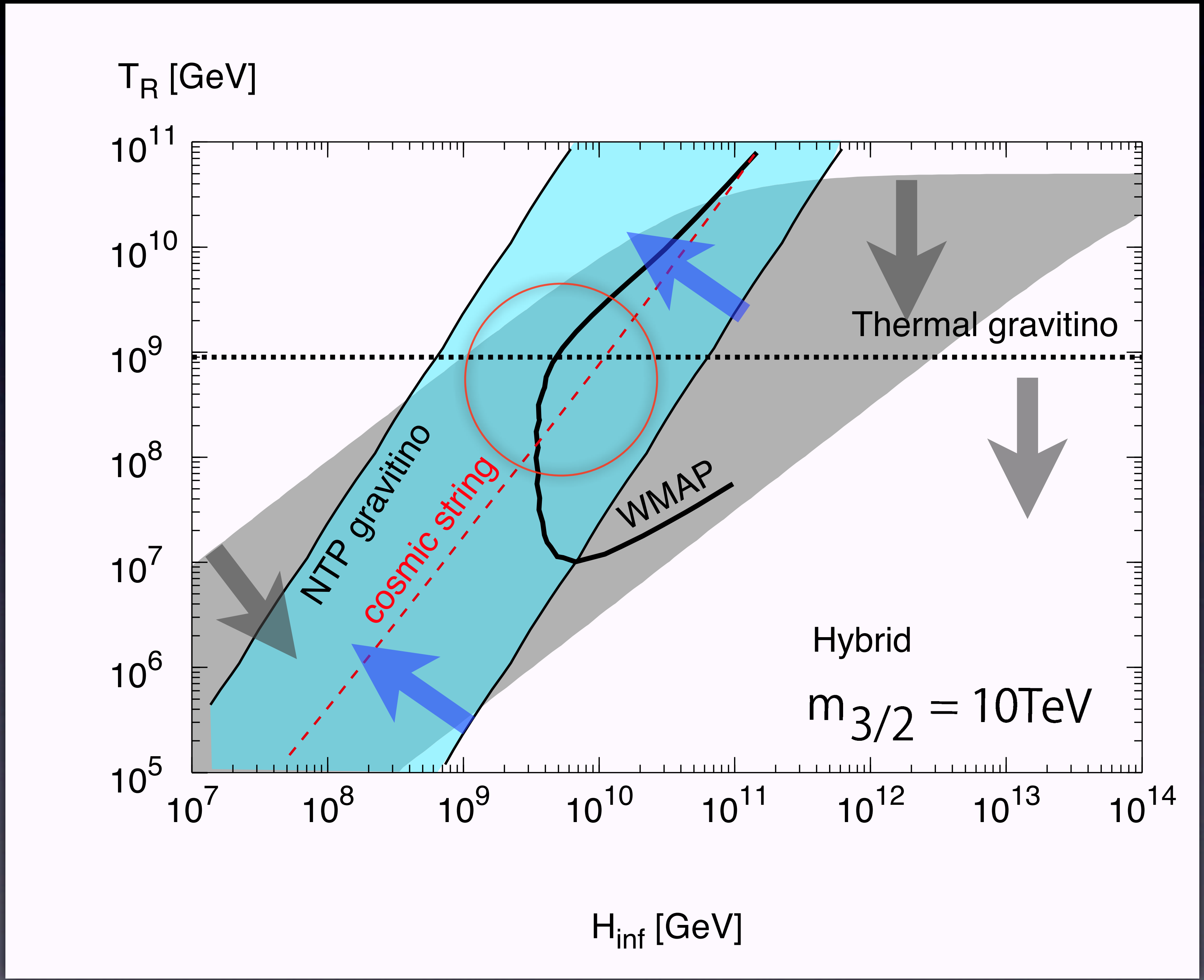
  → Polonyi Problem

We revive the conventional Polonyi model

Revive Polonyi Model

Assume enhanced coupling of Polonyi with inflaton X.

The Polonyi problem can be solved and it can be consistent with leptogenesis scenario.



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

Summary

- We derived correct expression for the moduli abundance under the adiabatic suppression mechanism.
- The result depends on inflation model.
- Polonyi problem can be solved for SUSY scale of O(10)TeV, which leads to 125GeV Higgs.
- Be careful on the abundance of scalar field.

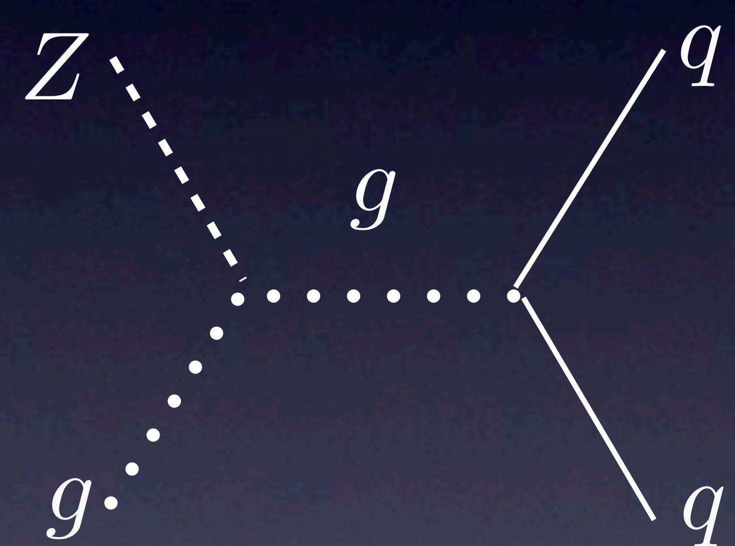
Backup Slides

Thermal Moduli

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

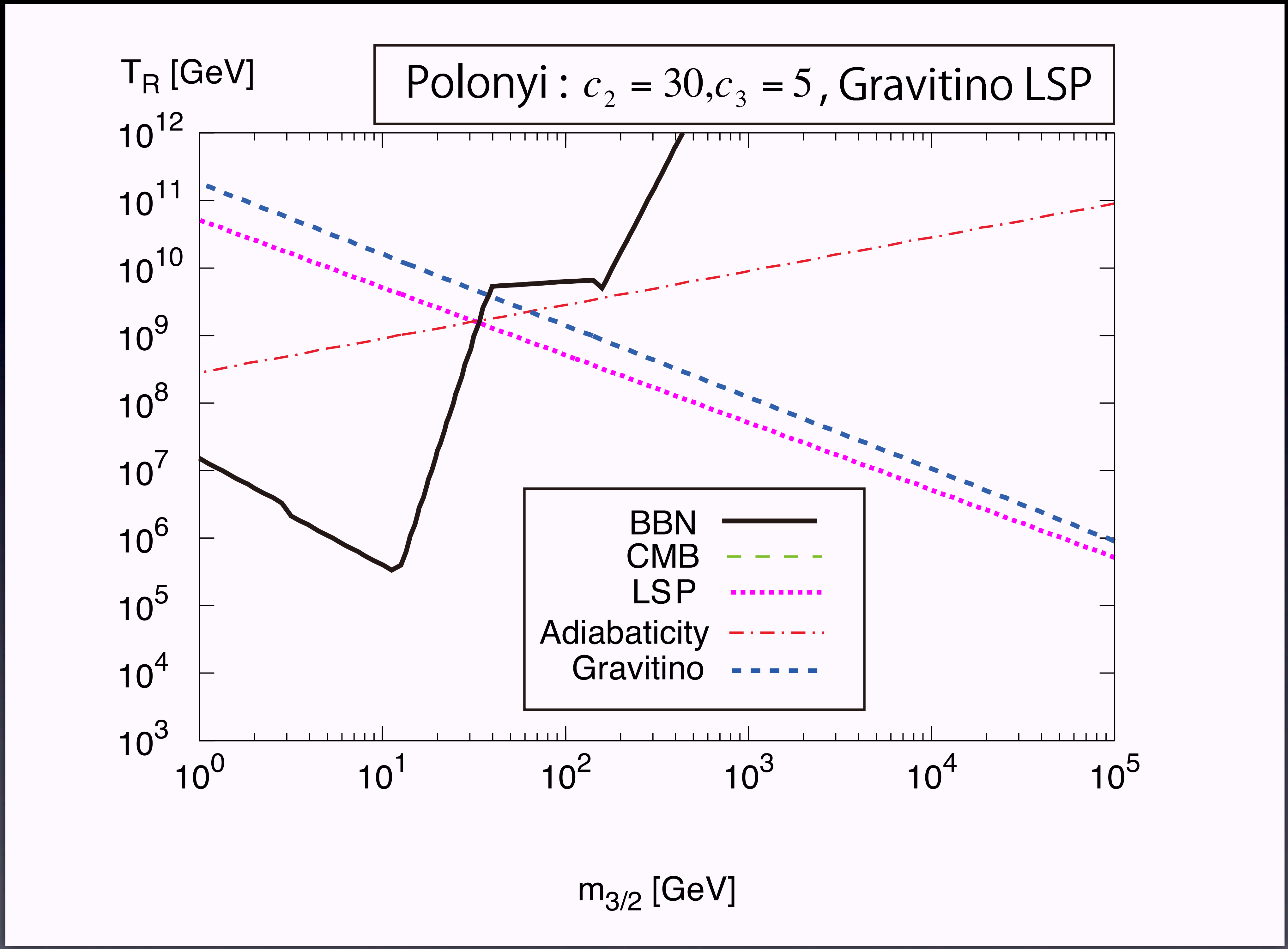
$$Y_Z \sim Y_{3/2} \sim 2 \times 10^{-12} \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right)$$

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



- 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.]

Moduli Problem

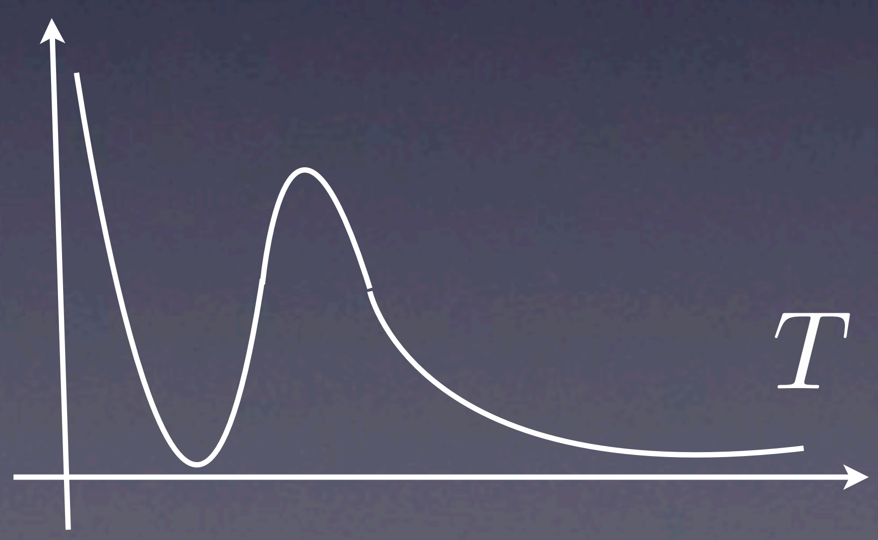
- Light scalar field in compactification of extra dimensions in String theory

- E.g. Kahler moduli in KKLT stabilization in type IIB string theory

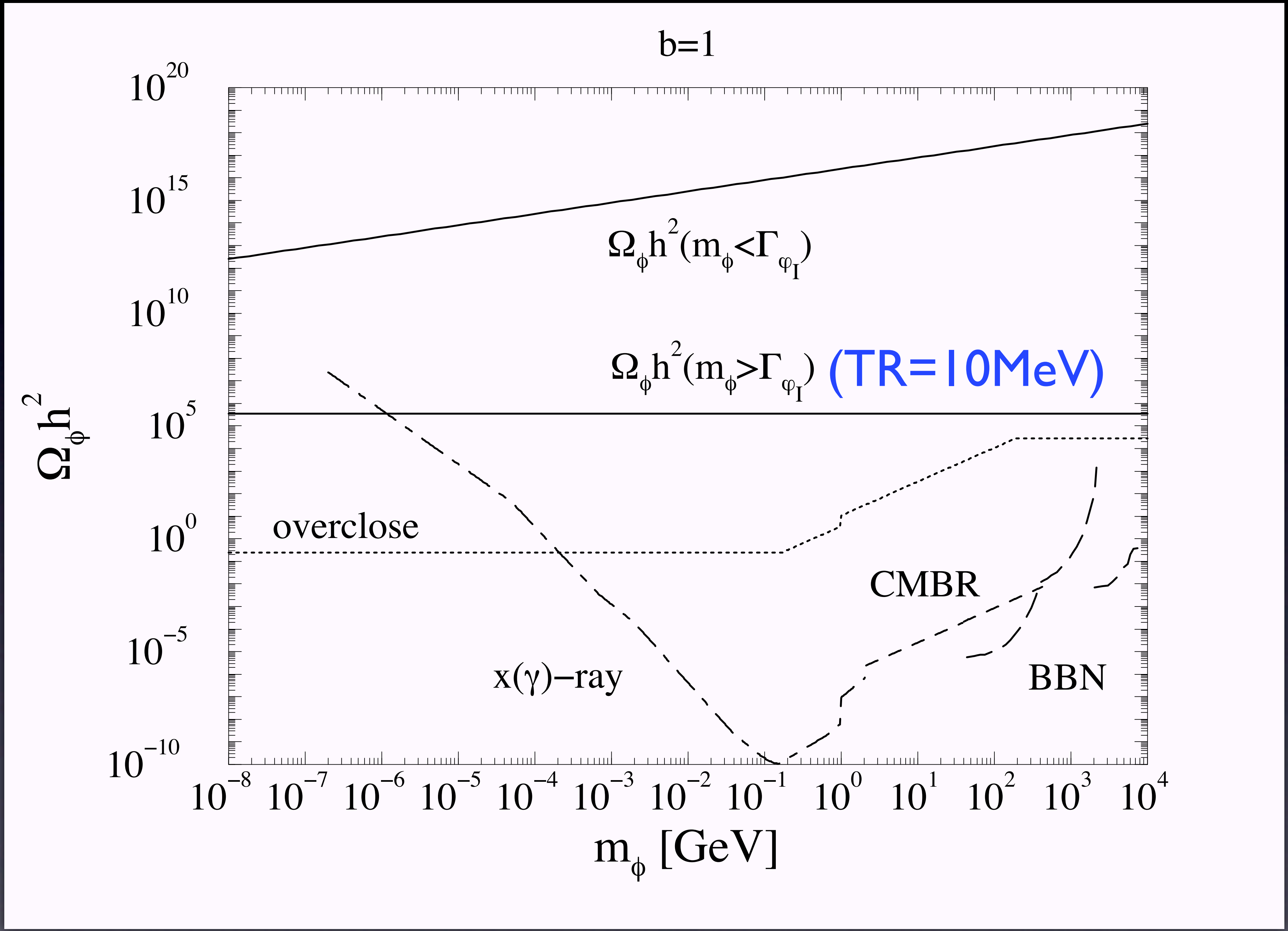
$$K = -3\ln(T+T^\dagger)$$

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

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



Constraint on the modulus abundance



[Asaka, Kawasaki (1999)]