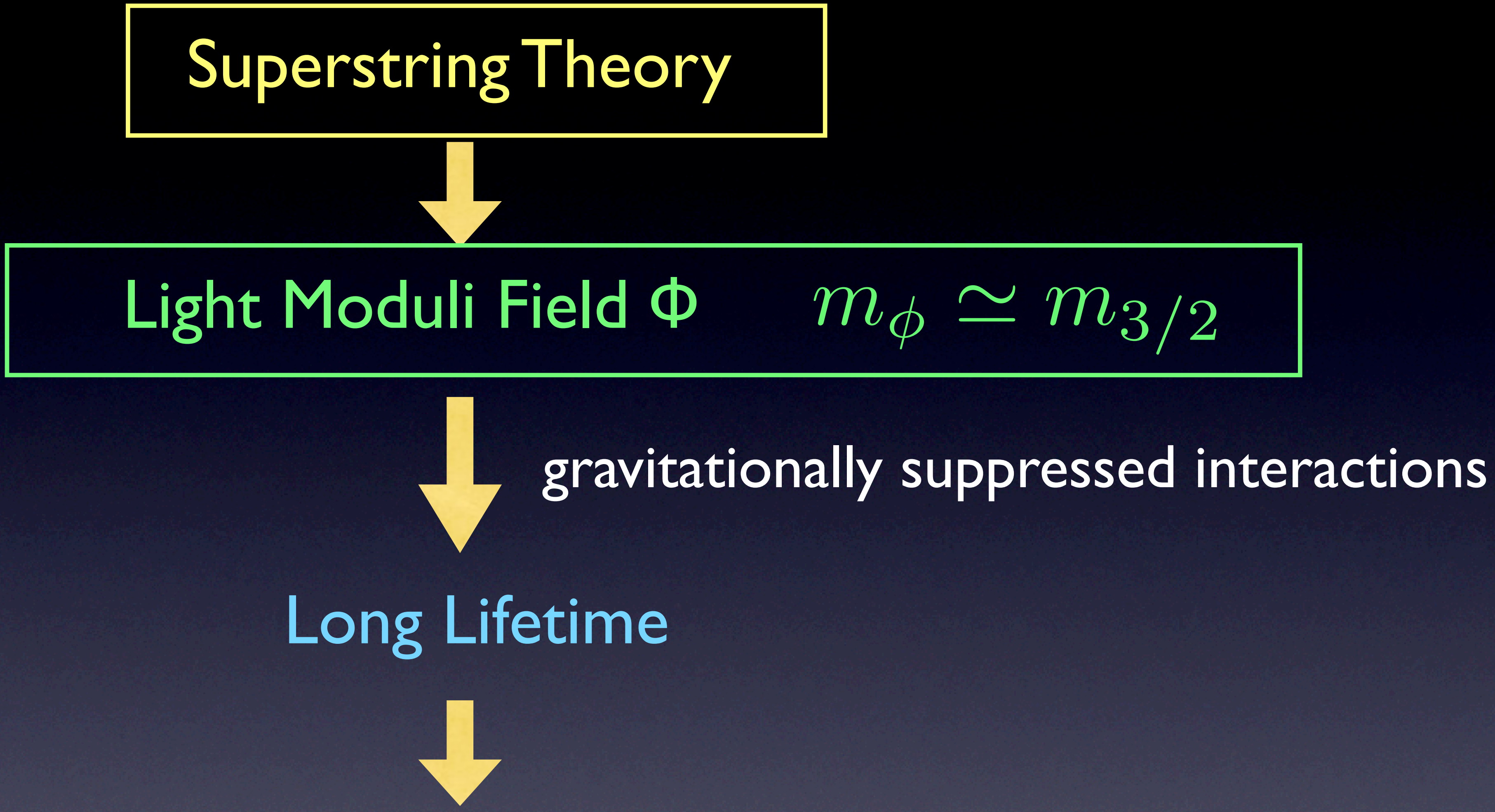
Finnish-Japanese Workshop on Particle Physics 2007

Moduli Problem, Thermal Inflation and Baryogenesis

Masahiro Kawasaki
Institute for Cosmic Ray Research
University of Tokyo

Cosmological Moduli Problem



Superstring Theory

Light Moduli Field Φ $m_\phi \simeq m_{3/2}$

gravitationally suppressed interactions

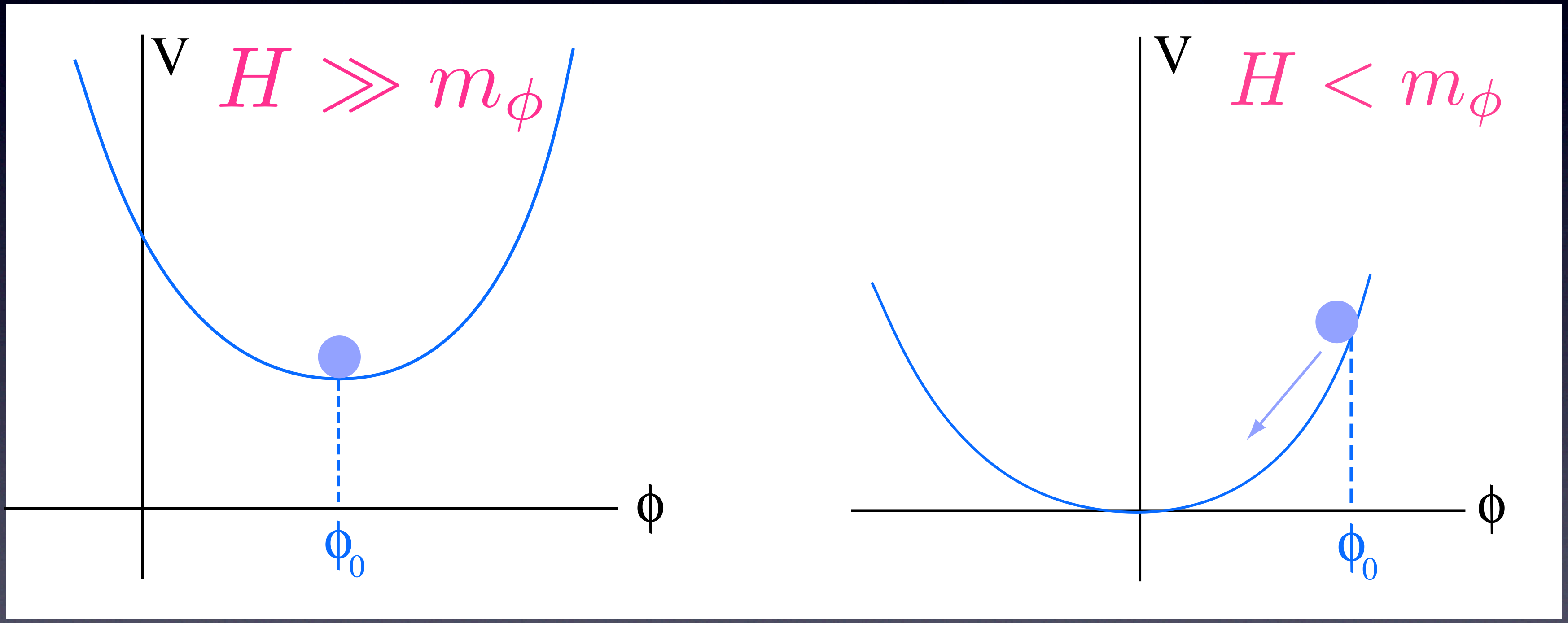
Long Lifetime

Cosmological Difficulty

- BBN
- Cosmic Density . . .

$$\boxed{V \simeq \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}H^2(\phi-\phi_0)^2}$$

Hubble induced mass



Moduli starts oscillation with large amplitude

$$\phi_0 \sim M_G \sim 10^{18}\mathrm{GeV}$$

Coughlan, Fischler, Kolb, Raby, Ross (1983) Banks et al (1994), de Carlos et al (1993)

- Cosmic Density

$$\boxed{\Omega_\phi \simeq 5 \times 10^{16} \left(\frac{m_\phi}{\mathrm{GeV}}\right)}$$

for stable moduli

- Moduli Decay

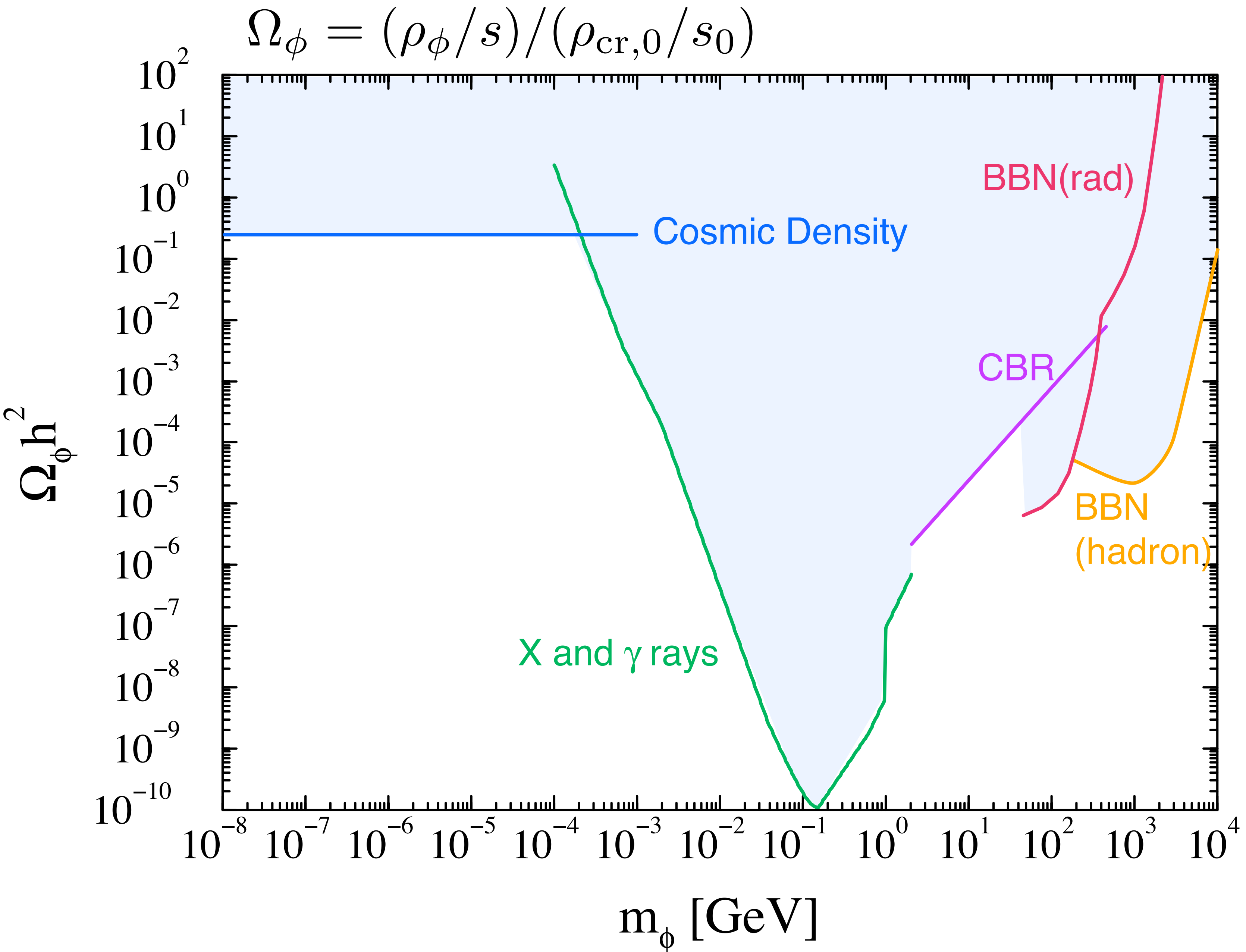
$$\boxed{\tau_\phi \sim \frac{M_{pl}}{m_\phi^2} \sim 10^{14}\,\mathrm{sec} \left(\frac{m_\phi}{\mathrm{GeV}}\right)^{-3}}$$

$m_\phi \lesssim 0.1\ \mathrm{GeV}$

  - Background Radiations(X-rays, γ-rays)
  - BBN (Destroy Light elements)
  - CBR (spectral distortion)

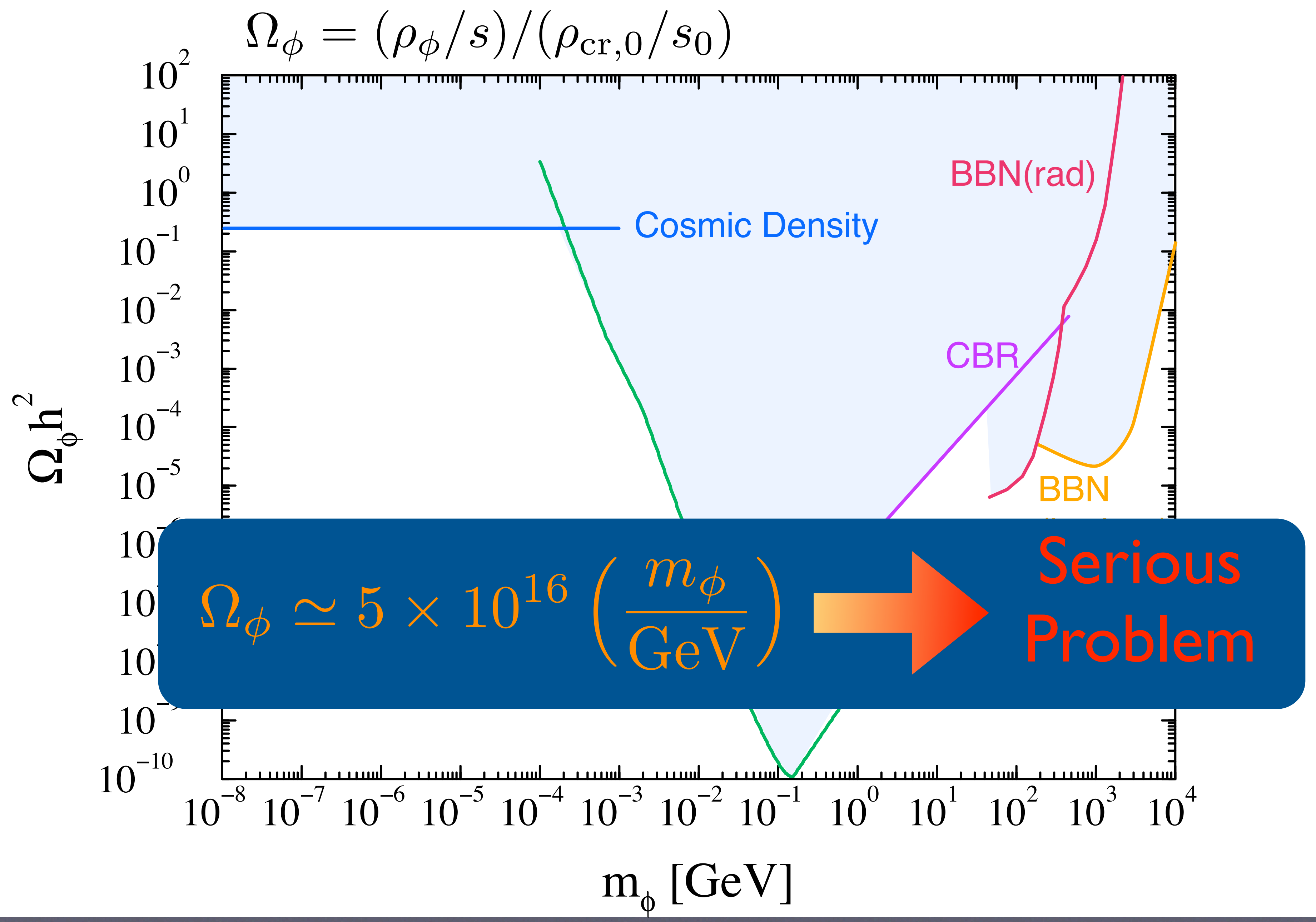
→ Constraints on Density

Cosmological Constraint



Asaka,MK (1999) + MK, Kohri, Moroi (2005) for BBN

Cosmological Constraint



$$\Omega_\phi = (\rho_\phi/s)/(\rho_{\mathrm{cr},0}/s_0)$$

$$\Omega_\phi \simeq 5\times 10^{16}\left(\frac{m_\phi}{\mathrm{GeV}}\right)$$

→ **Serious Problem**

Asaka, MK (1999) + MK, Kohri, Moroi (2005) for BBN

Solution to Moduli Problem

- Large Entropy Production → dilute moduli
  - Thermal Inflation Lyth, Stewart (1995)
  - Domain Wall Decay MK, F.Takahashi (2005)
- Others
  - Heavy Moduli
  - Large Hubble induced mass $V \sim CH^2\phi^2 \quad C \gg 1$ Linde (1996)
  - ....

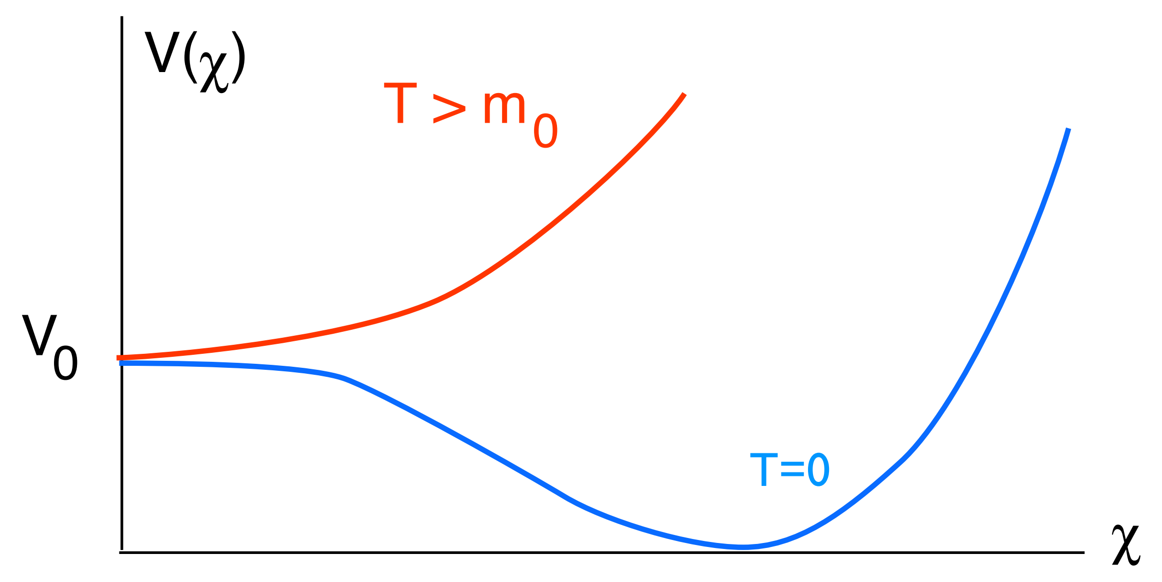
Thermal Inflation

Lyth, Stewart (1995) Yamamoto (1986)

Flaton (χ) potential

$$\boxed{V \simeq V_0 + (T^2 - m_0^2)|\chi|^2 + \frac{|\chi|^6}{M_*^2}}$$

finite temp



$m_0 \lesssim T \lesssim V_0^{1/4}$ → Vacuum energy dominates

→ Inflation with e-fold ~10

Thermal Inflation

→ dilute big bang moduli

Thermal Inflation

→ dilute big bang moduli

However,

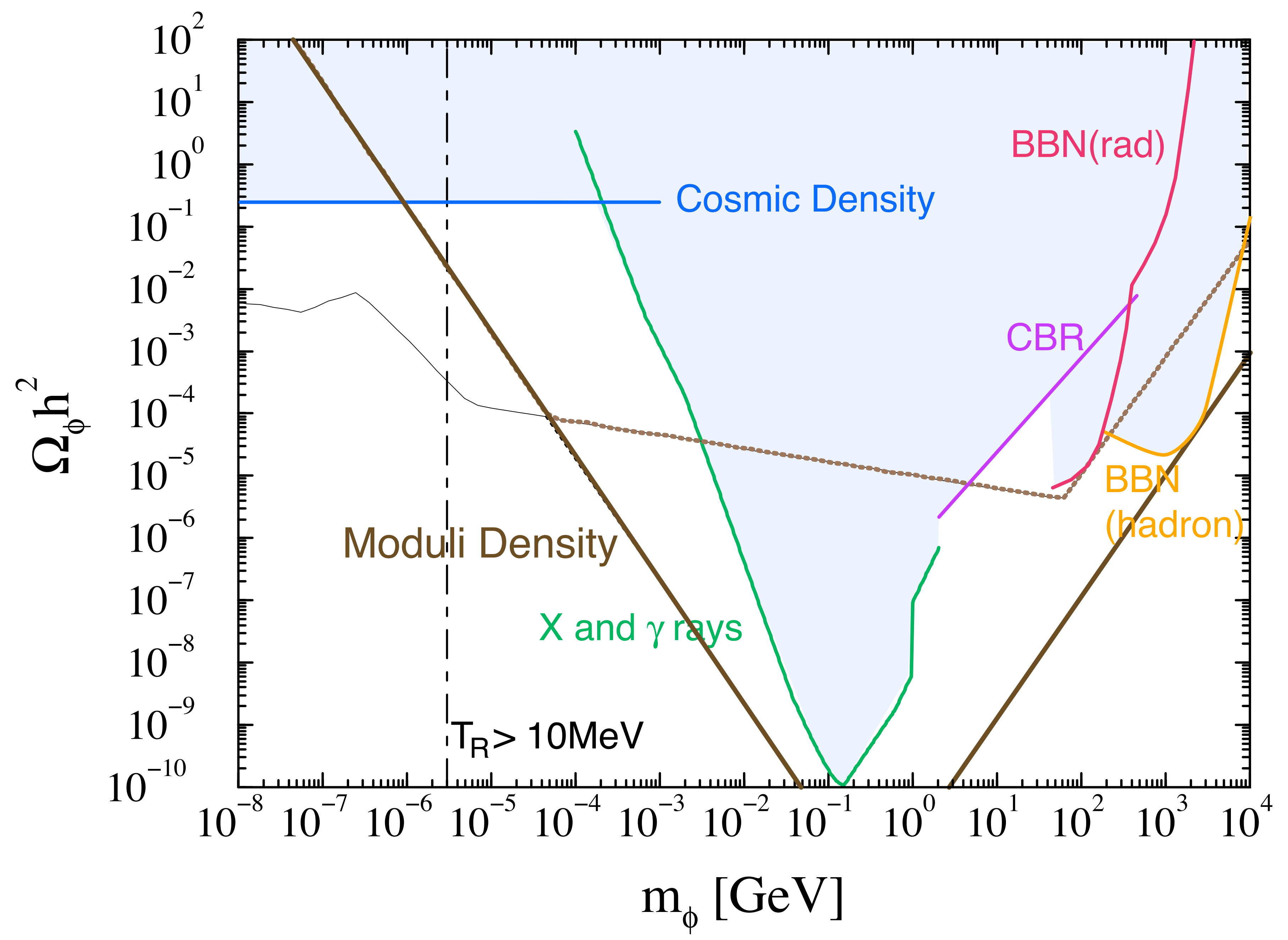
$$\boxed{\begin{aligned} V &\simeq \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}H^2(\phi-\phi_0)^2 \\ &\simeq \frac{1}{2}m_\phi^2\left(\phi + \frac{H^2}{m_\phi^2}\phi_0\right)^2 + \cdots \end{aligned}}$$

During TI the minimum of the potential deviates from 0

→ new oscillations of moduli

Moduli Density = Big Bang Moduli+TI Moduli

Minimum Moduli Density Predicted by TI



Hashiba, MK, Yanagida (1997) Asaka, MK (1999)

Baryon Number of the Universe?

Large entropy production with Low T_R → dilute pre-existing baryons

Most of conventional baryogenesis mechanisms may not work

Affleck-Dine baryogenesis → work for

$$m_\phi \lesssim O(10)\mathrm{MeV}$$

$$n_b/s \sim 2\times 10^{-9}\Omega_\phi(m_\phi/\mathrm{GeV})^{-1}$$

Baryon Number of the Universe?

Large entropy production with Low T_R → dilute pre-existing baryons

Most of conventional baryogenesis mechanisms may not work

Affleck-Dine baryogenesis → work for

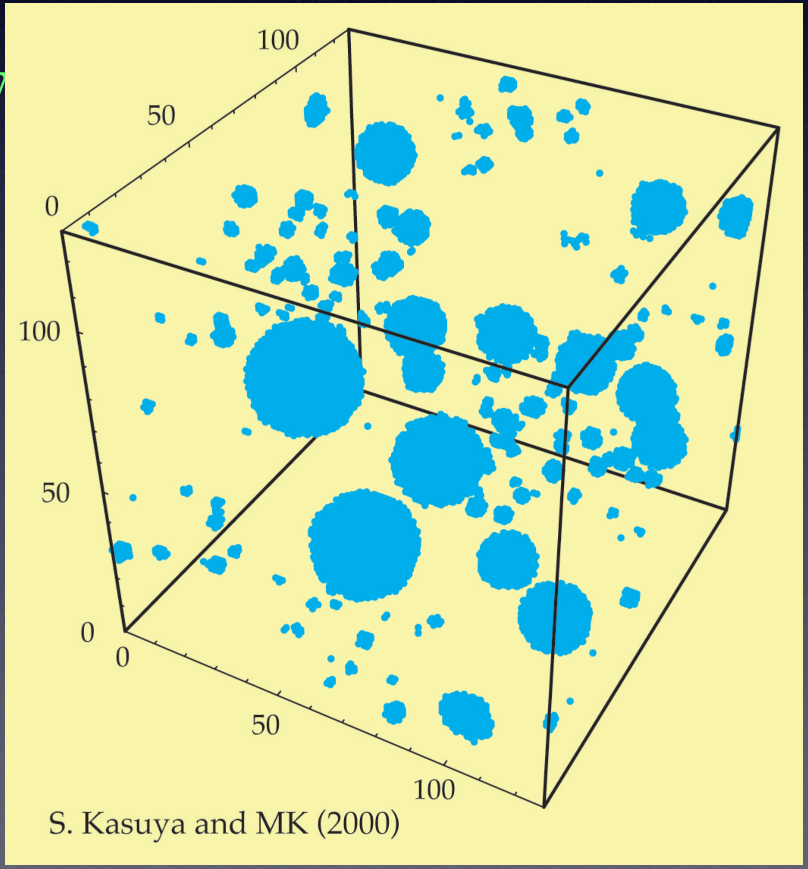
$$m_\phi \lesssim O(10)\mathrm{MeV}$$

$$n_b/s \sim 2 \times 10^{-9}\Omega_\phi(m_\phi/\mathrm{GeV})^{-1}$$

However,

Q-ball Formation

→ Obstacle to AD



S. Kasuya and MK (2000)

Late-time Affleck-Dine

Stewart, MK, Yanagida (1996)
Joeng et al (2004)

Leptogenesis by LH_u Flat Direction

Superpotential

MSSM

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

χ Flaton

neutrino mass

μ term for $\langle\chi\rangle \neq 0$

LH_u has a large vev after thermal inflation

→ Leptogenesis

Scalar Potential of Flat Directions

$$V = V_F + V_D + V_{SB} \qquad L = \begin{pmatrix} 0 \\ l \end{pmatrix}, H_u = \begin{pmatrix} h_u \\ 0 \end{pmatrix}, H_d = \begin{pmatrix} h_d & 0 \end{pmatrix}$$

- F-term $V_F =$

$$\frac{1}{M^2}\Big\{|\lambda_\chi \chi^3 + 2\lambda_\mu \chi h_u h_d|^2 + |\lambda_\nu l h_u^2|^2$$

$$+\underline{|\lambda_\mu \chi^2 h_d + \lambda_\nu l^2 h_u|^2} + |\lambda_\mu \chi^2 h_u|^2\Big\}$$

- D-term

$$V_D = \frac{g^2}{2}\left(|h_u|^2 - |l|^2 - |h_d|^2\right)^2$$

$\not{L}$

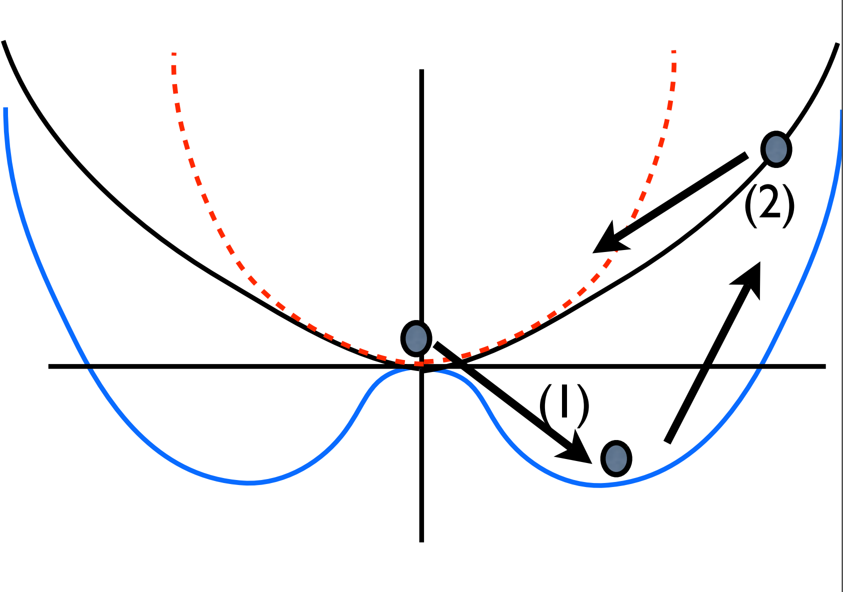
- Soft SUSY breaking terms

$$V_{\rm SB} = V_0 - m_\chi^2|\chi|^2 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2$$

$$+\left\{\frac{A_\chi\lambda_\chi}{4M}\chi^4 + \frac{A_\mu\lambda_\mu}{M}\chi^2 h_u h_d + \underline{\frac{A_\nu\lambda_\nu}{2M} l^2 h_u^2} + \text{c.c.}\right\}$$

→ CP phase $\arg(\lambda_\mu \lambda_\nu^*)$ $\arg(\lambda_\chi \lambda_\mu^*)$

Dynamics of Flat Directions



(1) At the end of thermal inflation

$\chi = 0$ $\boxed{m^2_{LH_u} \simeq m^2_L - m^2_{H_u} < 0}$

LH_u flat direction rolls away from the origin

(2) Flaton rolls down

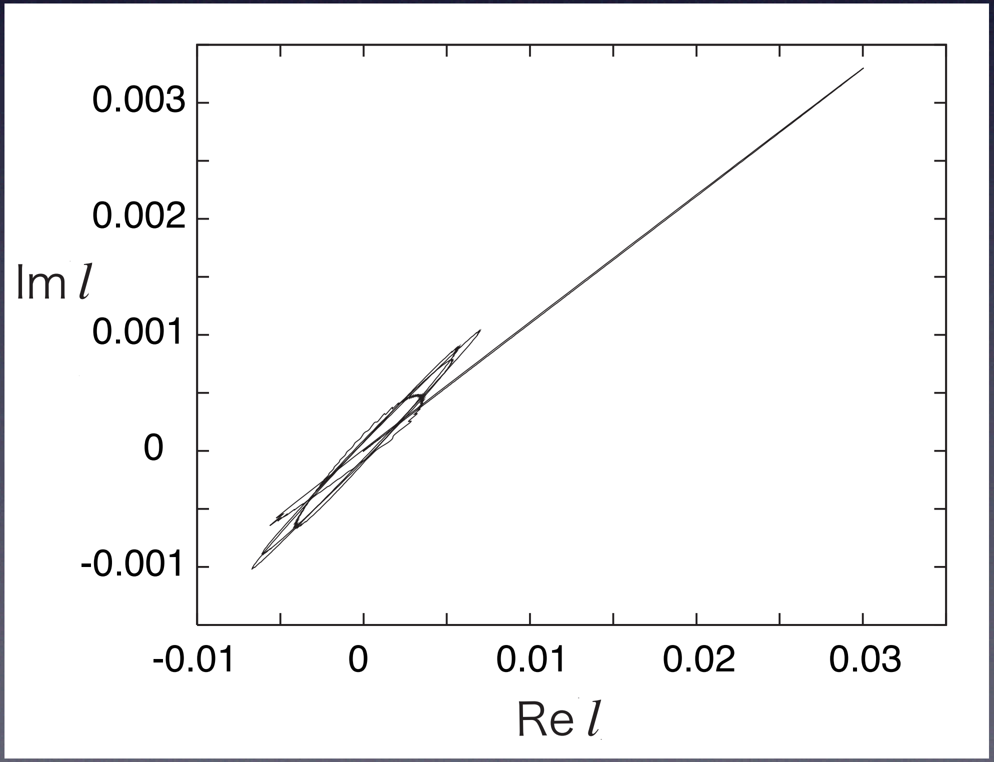
$\langle \chi \rangle = \chi_0 \longrightarrow \mu$ term

$$\boxed{m^2_{LH_u} \simeq m^2_L - m^2_{H_u} + |\mu|^2 > 0}$$

$\Downarrow$

LH_u direction starts to rotate

Lepton number generation

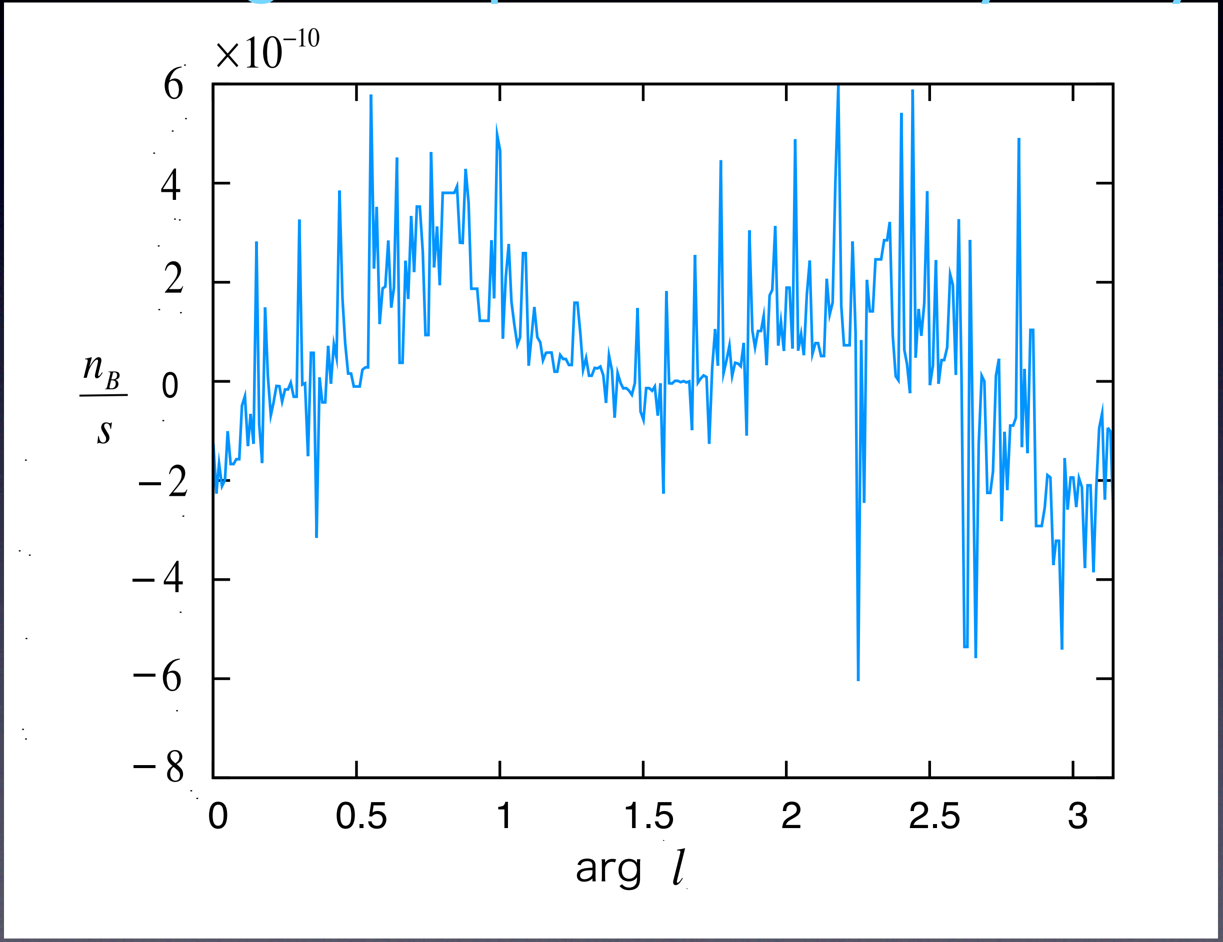


Lattice Calculation

Nakayama, MK (2006)

We studied the full dynamics by using lattice simulation including all relevant scalar fields

Initial angular dependence of baryon asymmetry



$T_R = 1$ GeV

$\arg(\lambda_\mu \lambda_\nu^*) = \pi/16$

⬇

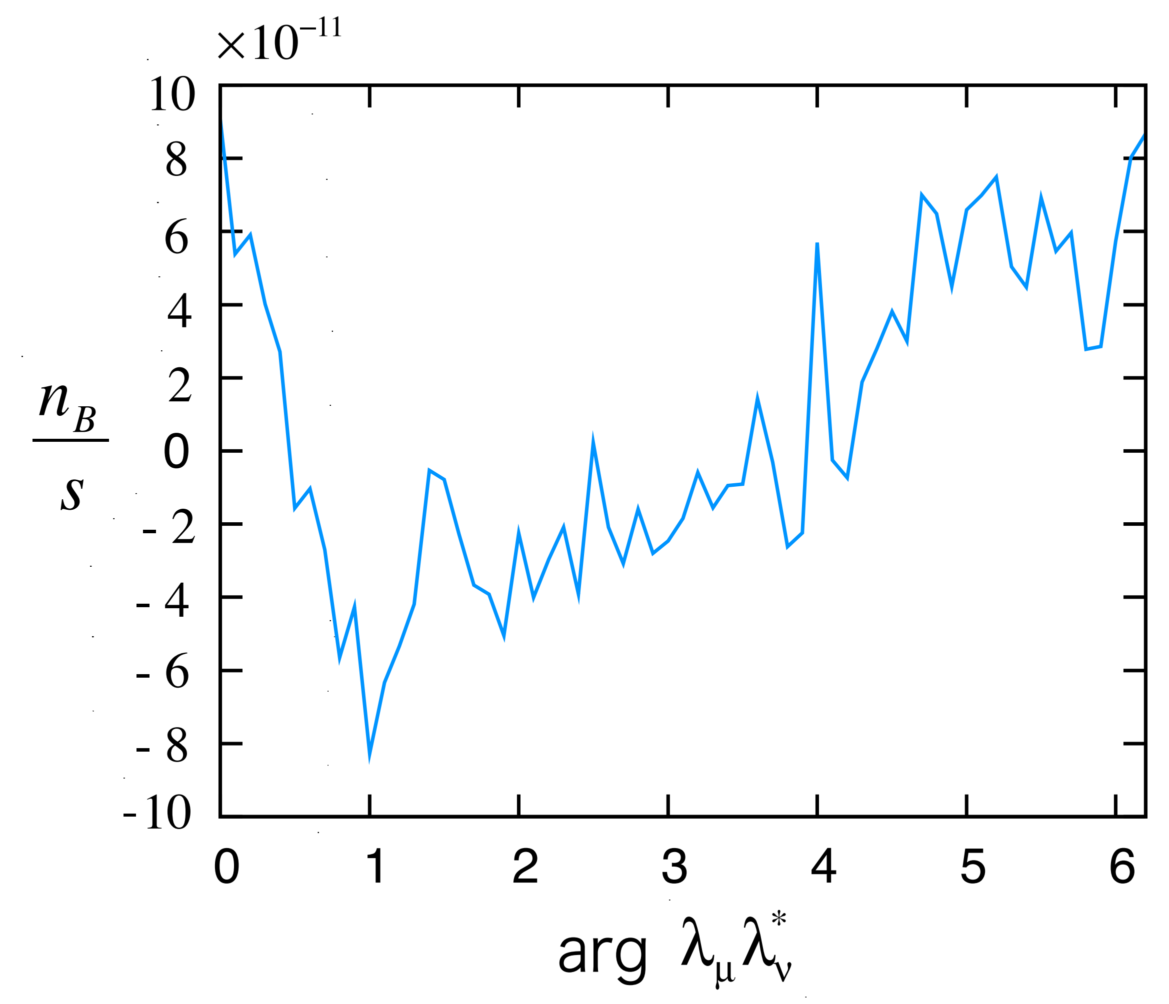
net baryon asym

$\lambda_\mu = 35 \quad \lambda_\nu = 10^4$

$$m_\chi = 180 \text{ GeV}, \; m_{H_u} = 700 \text{ GeV}, \; m_{H_d} = 800 \text{ GeV}, \; m_L = 640 \text{ GeV},$$

$$\lambda_\chi = 4, \; A_\mu = 450 \text{ GeV}, \; A_\nu = 200 \text{ GeV}, \; A_\chi = 20 \text{ GeV}, \; \arg(\lambda_\chi \lambda_\mu^*) = -\pi/4$$

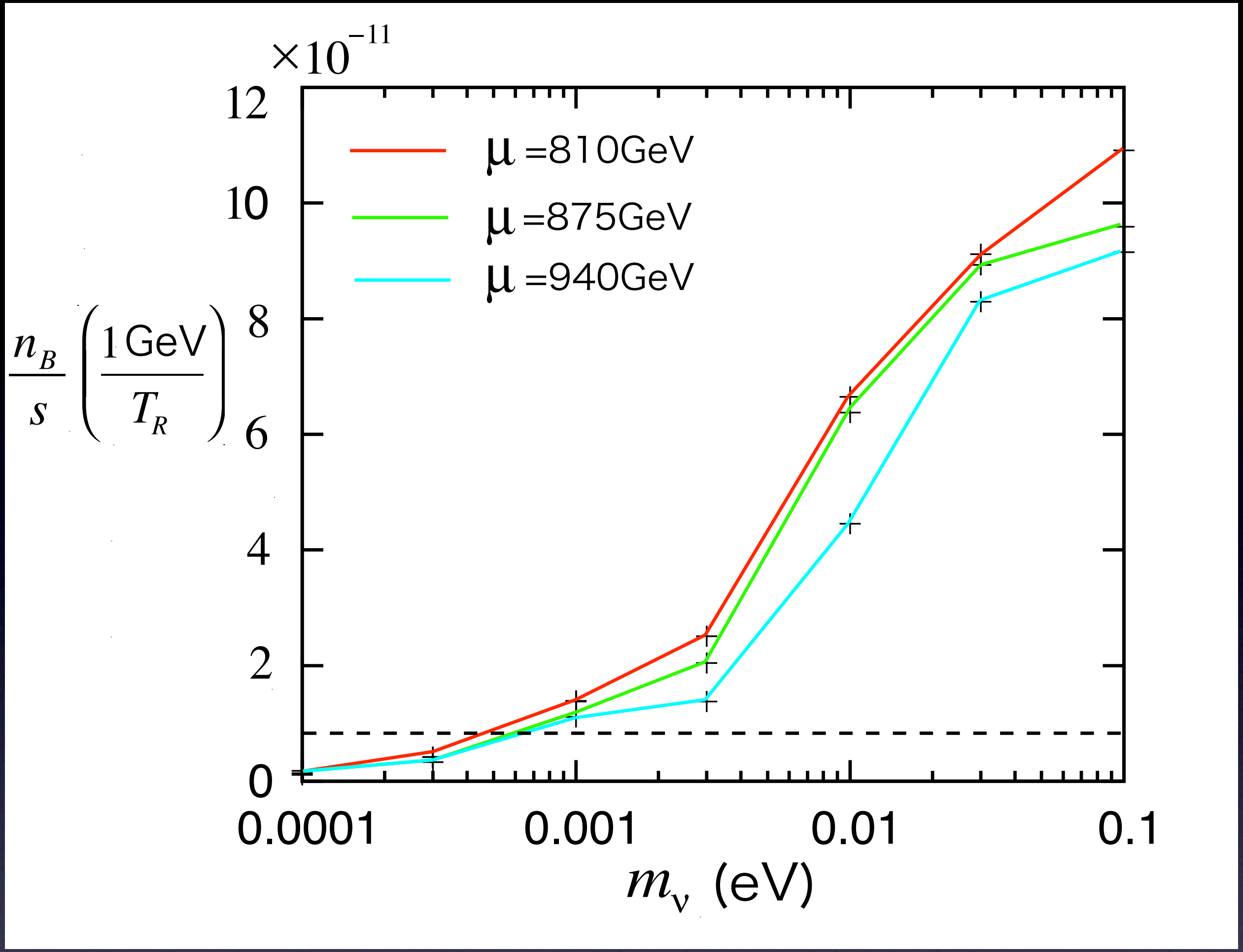
Resultant baryon asymmetry vs CP violation



$\arg(\lambda_\mu \lambda_\nu^*) = \pi/4, 5\pi/4$

$\longrightarrow$ no CP violation

Net baryon asymmetry can be created due to $\cancel{CP}$



$$\mu = \lambda_\mu \frac{\phi_0^2}{M}$$

$$m_\nu = \lambda_\nu \frac{\langle h_u \rangle^2}{M}$$

$\mu \sim 800 - 840$ GeV

$m_\nu \sim 10^{-3} - 10^{-1}$ eV

→ This scenario works

However, we only investigated restricted parameter space

Conclusion

- Moduli Problem is solved by thermal inflation
- However, baryon number is also diluted by thermal inflation
- Baryon number can be re-generated through late-time AD mechanism