HIGGS INFLATION, VACUUM STABILITY, AND LEPTOGENESIS

JHEP **08** (2020) 072 (arXiv: 2001.07032)
Also see Phys. Lett. B **785**, 184-190 (2018) and Mod. Phys. Lett. A **33**, no. 17, 1850097 (2018)

Kimiko Yamashita
(Institute of High Energy Physics
Chinese Academy of Sciences)

Collaborators:

Neil D. Barrie (IBS-CTPU)
Akio Sugamoto (Ochanomizu Univ.)
Tatsu Takeuchi (Virginia Tech.)

HPNP Special Edition 2021
March 25th 2021
Osaka University

Table of contents

Model

- Particle Content Beyond the SM

1. Three generations of right-handed neutrinos ν_R
2. Complex scalar field ϕ with L=2

Model

Φ: Higgs doublet

$\widetilde{\Phi} = i\sigma_2 \Phi^*$

1. Interactions with ν_R:

$$\mathcal{L}_{\phi,\nu_R} = \left(g\, \phi^* \overline{\nu_R^c} \nu_R + y\, \overline{L}\, \widetilde{\Phi} \nu_R \right) + \mathrm{h.c.}$$

- Lepton number preserving form
- $\phi \to 2\nu_R$, $\nu_R \to h + \nu_L$, and L converts into B
- Active neutrino masses are generated after ϕ and Φ take the vevs

Model

2. Interactions between ϕ and Φ—Dim-4

$$V(\Phi,\Phi^\dagger,\phi,\phi^\dagger) = \lambda_h\left(\frac{v_h^2}{2}-\Phi^\dagger\Phi\right)^2 + \lambda_\phi\left(\frac{v_\varphi^2}{2}-\phi^\dagger\phi\right)^2$$
$$+\underline{\underline{\kappa\left(\frac{v_h^2}{2}-\Phi^\dagger\Phi\right)\left(\frac{v_\varphi^2}{2}-\phi^\dagger\phi\right)}} - \underline{\underline{\epsilon_\theta\phi^\dagger\phi\left(\phi-\phi^\dagger\right)^2}}$$

Higgs Portal Interaction

$\not{L}$ *

* global U(1) transformation:

$$\phi \to e^{2i\alpha}\phi$$

3. Interactions between ϕ and Φ—Dim-6

$$\mathcal{L}_{\not{CP}}(\Phi,\Phi^\dagger,\phi,\phi^\dagger) = \frac{2g^{\mu\nu}}{\Lambda^2}\left(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\right)\partial_\nu\left(\Phi^\dagger\Phi\right)$$

$\not{C}$ $\not{CP}$

Model

4. Non-minimal interactions with gravity

Jordan frame

$$S_J = \int d^4x\sqrt{-g}\Big[-\frac{M_p^2}{2}R - \xi\Phi^\dagger\Phi R - \zeta\phi^\dagger\phi\, R + g^{\mu\nu}\,\partial_\mu\Phi^\dagger\,\partial_\nu\Phi + g^{\mu\nu}\,\partial_\mu\phi^\dagger\,\partial_\nu\phi$$

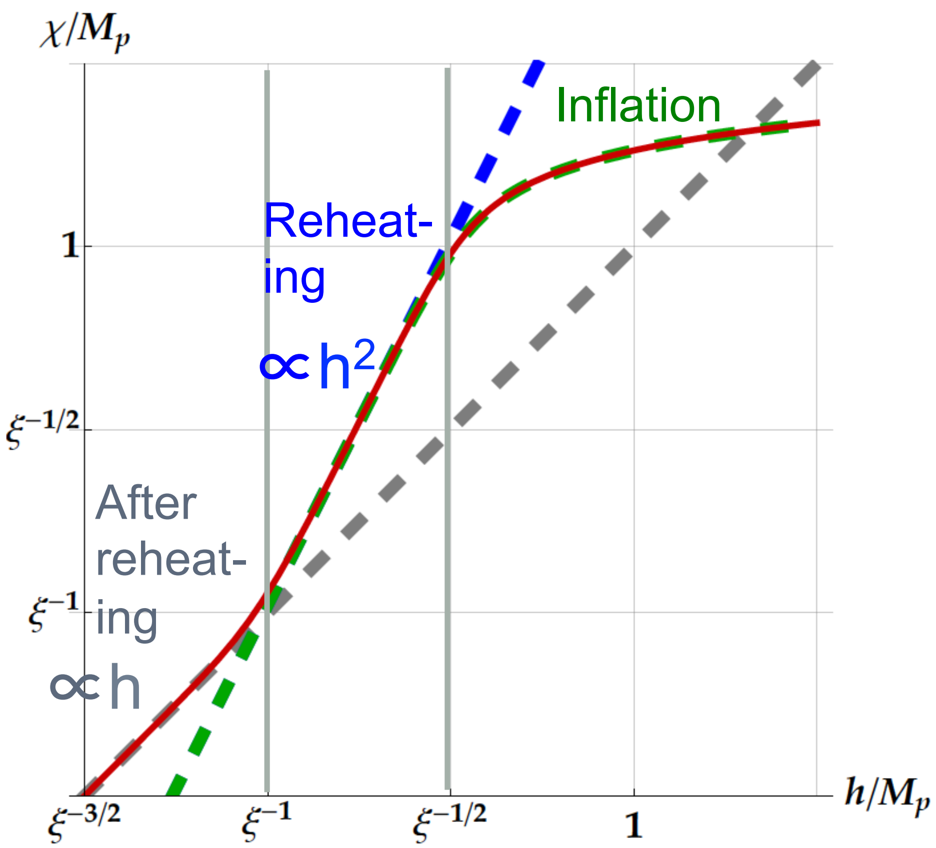
$$- V(\Phi,\Phi^\dagger,\phi,\phi^\dagger) + \mathcal{L}_{\phi,\nu_R} + \cdots\Big] + \cdots$$

Higgs Inflation

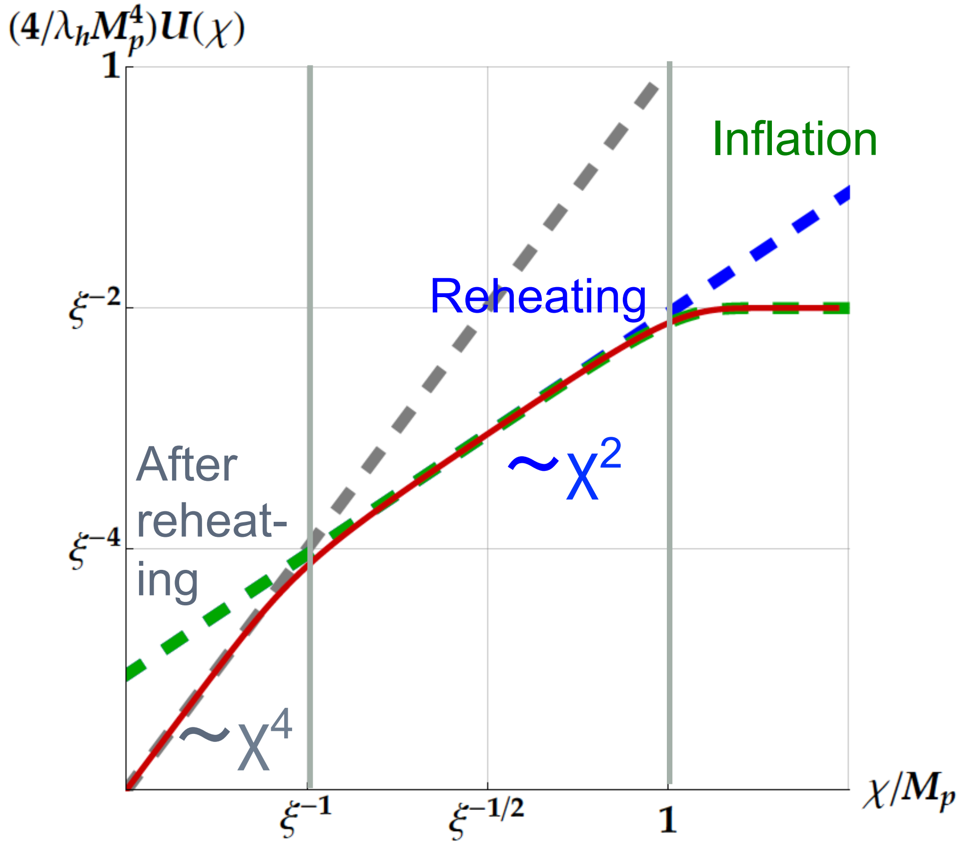
Review

Einstein frame

$$S_E = \int d^4x \sqrt{-\tilde{g}} \left[-\frac{M_p^2}{2}\tilde{R} + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\chi\,\partial_\nu\chi - U(\chi) + \cdots \right]$$



(a) Higgs-Inflaton relation

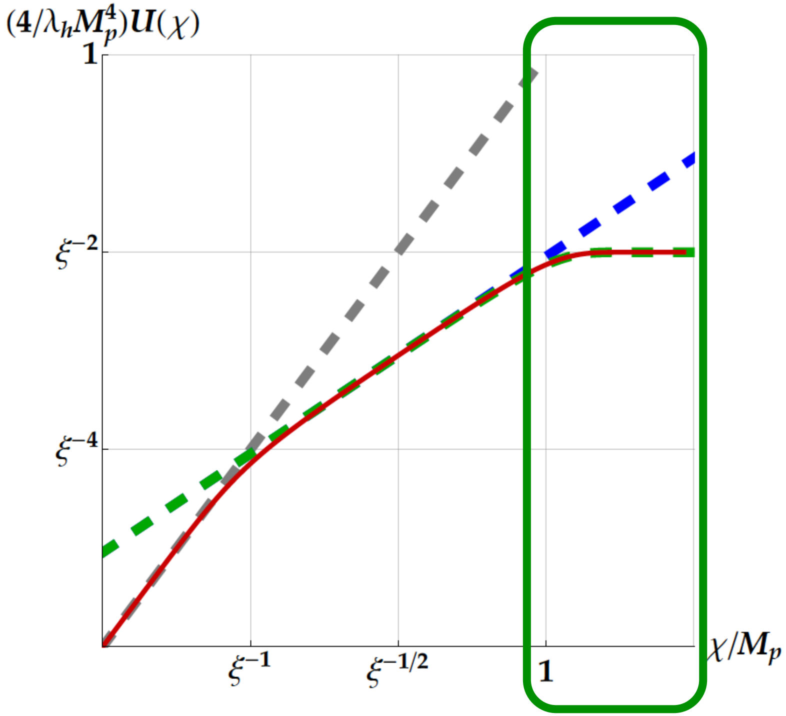


(b) Effective Inflaton Potential

Review

Higgs Inflation

- If $\lambda_h<0$ at a high scale, cannot to support the slow roll of the Higgs towards a potential minimum



(b) Effective Inflaton Potential

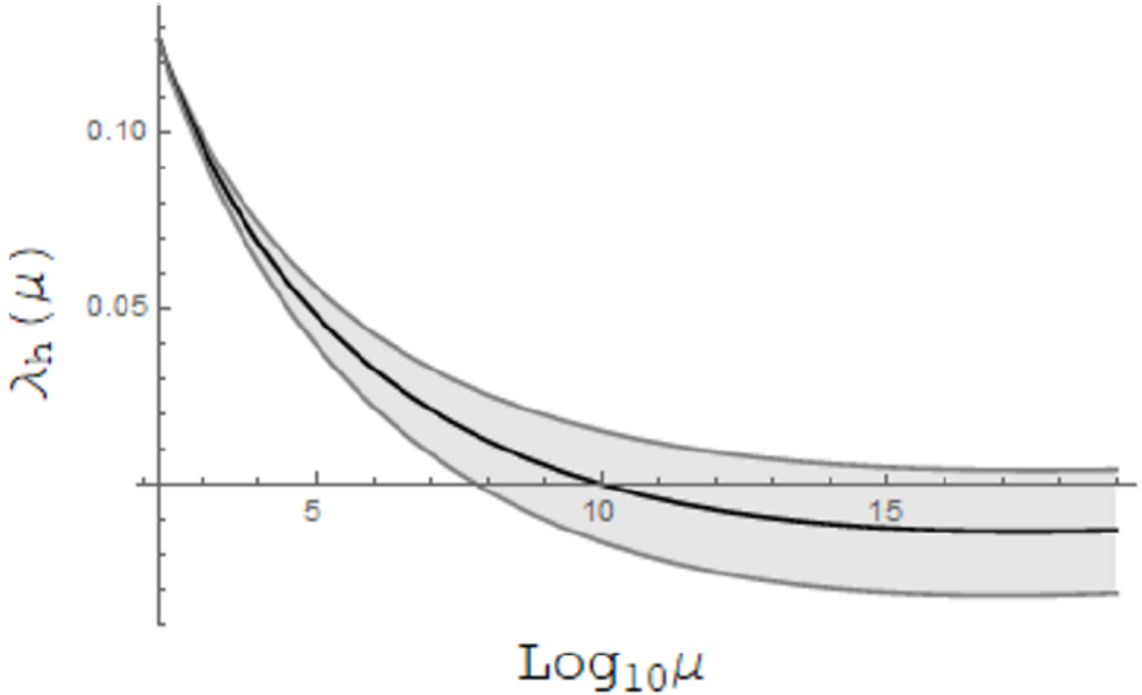
Recall that $\mu_{\rm inf}^2 = \dfrac{\lambda_h M_p^2}{3\,\xi^2}$

$$U(\chi) \approx \begin{cases} \frac{1}{4}\lambda_h \chi^4 & \text{for } \frac{\chi}{M_p} \ll \frac{1}{\xi} \quad \text{(after reheating)} \\ \frac{1}{2}\mu_{\rm inf}^2 \chi^2 & \text{for } \frac{1}{\xi} \ll \frac{\chi}{M_p} \ll 1 \quad \text{(reheating)} \\ \frac{3}{4}\mu_{\rm inf}^2 M_p^2 \left[1 - e^{-\sqrt{\frac{2}{3}}(\chi/M_p)}\right]^2 & \text{for } 1 \ll \frac{\chi}{M_p} \quad \text{(inflation)} \end{cases}$$

Review

Vacuum Stability

- SM



$\lambda_h^{\text{SM}}(M_p) \simeq -0.013$

$$\lambda_h^{\text{SM}}(m_H) = 0.13$$

$$m_H = 125.10 \pm 0.14\,\text{GeV}$$

$$m_t = 173.1 \pm 0.9\,\text{GeV}$$

Vacuum Stability

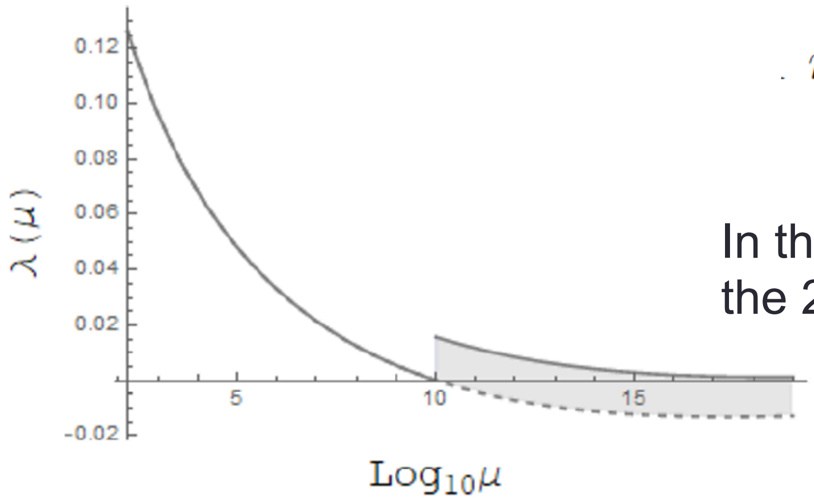
V: $\kappa(\Phi^\dagger\Phi)(\phi^\dagger\phi) \rightarrow \frac{\kappa}{4}h^2\varphi^2$ and $\frac{\lambda_\phi}{4}(v_\varphi^2 - \varphi^2)^2$ $\phi = \frac{1}{\sqrt{2}}\varphi\, e^{i\theta}$

At $\mu = m_\varphi$, the integrating out of the φ degree of freedom leads to a finite shift:

$$\lambda_h^{\rm SM}(m_\varphi) = \lambda_h(m_\varphi) - \frac{\kappa^2(m_\varphi)}{4\lambda_\phi(m_\varphi)}$$

J. Elias-Miro, J.R. Espinosa, G.F. Giudice, H.M. Lee and A. Strumia, JHEP **06** (2012) 031

- For $\mu < m_\varphi$, the running coupling is that of the SM: $\lambda_h(\mu) = \lambda_h^{SM}$
- For $\mu > m_\varphi$ it runs with contributions from φ



$$m_\varphi = 10^{10}\,\text{GeV}$$
$$\kappa = 2.5\times 10^{-4} \quad , \lambda_\phi = 10^{-6}$$

In the numerical calculations the 2-loop RGEs for the SM couplings are used

A. Salvio, Phys. Rev. D **99** (2019) 015037

Review

Leptogenesis

Baryon asymmetry

- Baryon number and anti-baryon number are NOT equal
- Baryon-to-photon ratio:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

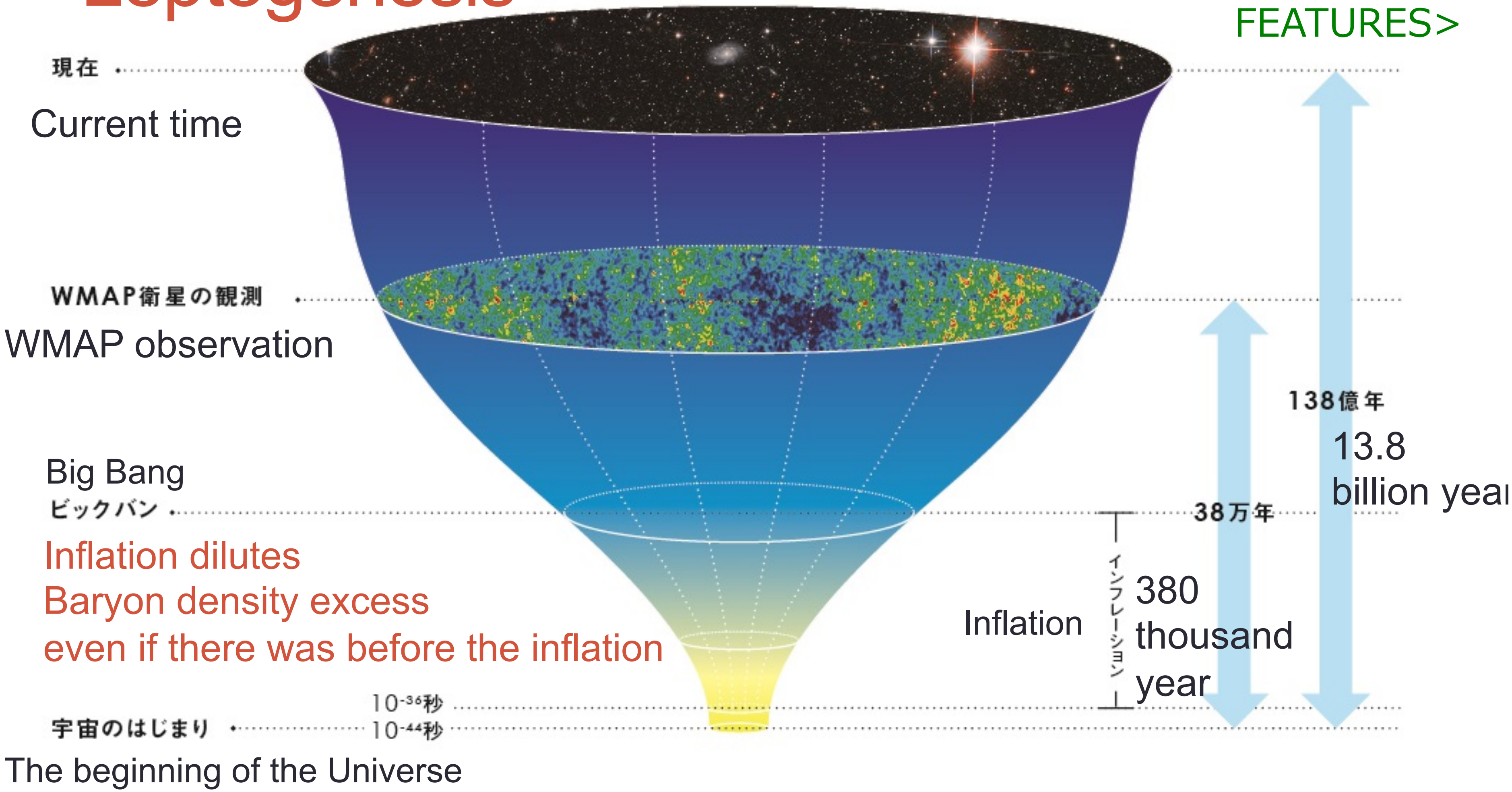
Nonzero

n_γ: photon number density
n_b: baryon number density
$n_{\bar{b}}$: anti-baryon number density

Review

Leptogenesis

<The University of Tokyo・Faculty of Science FEATURES>



After the inflation, Baryon is created larger number than the anti-baryon particles → Baryogenesis mechanism is required

Review

Leptogenesis

Standard Model

↓

Electroweak Baryogenesis is possible?

- CP violation amount is small
- SM doesn't satisfy Sakharov's third condition

A. D. Sakharov, JETP Lett. 5, 24(1967)

Sakharov's conditions
(Requirements for the Baryogenesis mechanism)

1. B violation
2. C and CP violation
3. Out of thermal equilibrium

We need to Beyond the SM

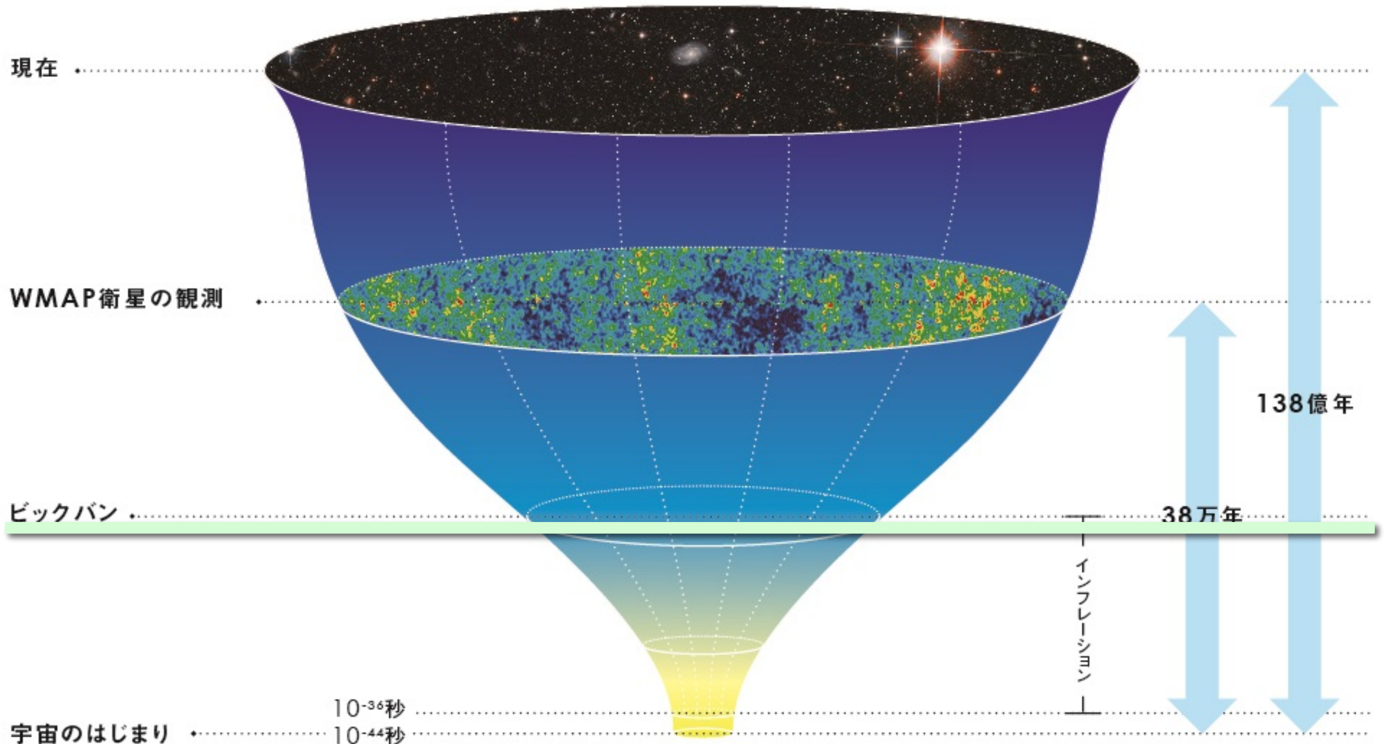
Big mystery for the Universe
regarding the matter origin

Leptogenesis

ν_R:Right-handed neutrino
($\varphi \to 2\nu_R$,
$\nu_R \to h+\nu_L$)

$\Delta(B-L)=0$
$\Delta(B+L)\neq 0$
→ Baryogenesis

Leptogenesis during reheating after inflation

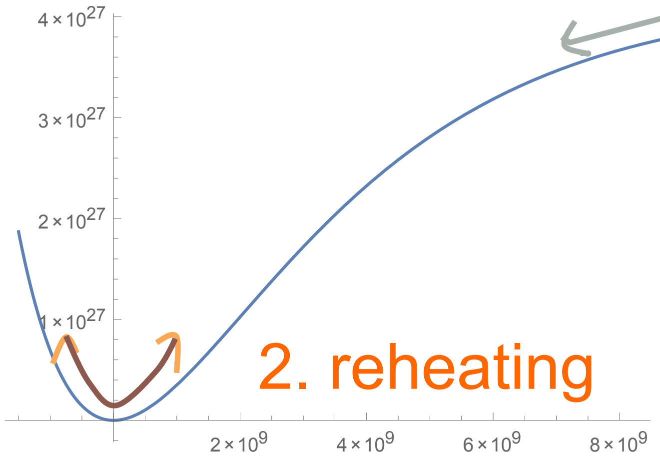


<The University of Tokyo・Faculty of Science FEATURES>

Leptogenesis

$U(\chi)$

1. inflation



2. reheating

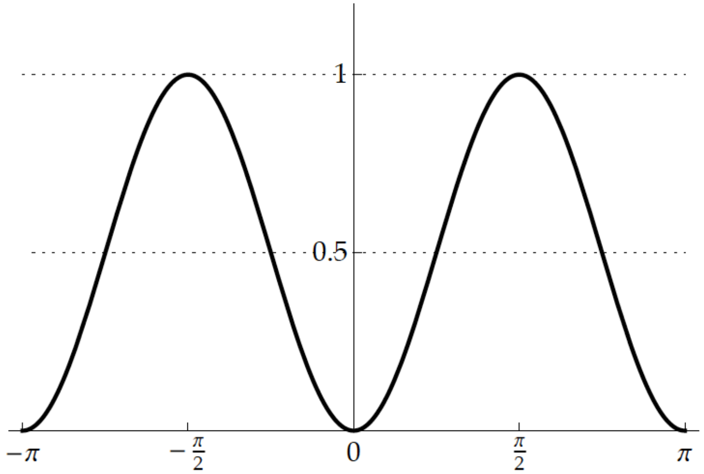
χ

~~thermal equilibrium~~

$$\frac{\varphi^2}{\Lambda}\partial_\mu\theta\partial^\mu\chi$$

~~C~~, ~~CP~~

$V/\varepsilon_\theta\varphi^4$



θ

~~L~~

$$V(\varphi,\theta) = \epsilon_\theta\, \varphi^4 \sin^2\theta$$

Leptogenesis

$$\phi = \frac{1}{\sqrt{2}}\varphi\, e^{i\theta}$$

- Our model

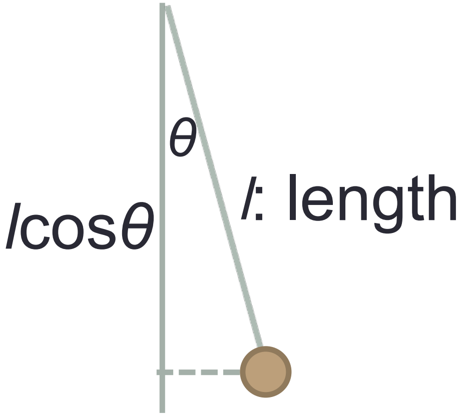
$$\ddot{\theta} + 3H\dot{\theta} + p\sin(2\theta) = -q(t)\cos[\mu(t - t_i)]$$

$$j_L^0 = -2\varphi^2\dot{\theta}$$

force by scalar potential

force by inflaton

- Swing with forced oscillation



$$ml^2\ddot{\theta} = -mgl\sin\theta + A\cos\omega t$$

Similar to force by scalar potential

Similar to force by inflaton

Leptogenesis

$$\phi = \frac{1}{\sqrt{2}}\varphi e^{i\theta} \quad \Lambda_{\not{C}\not{P}} \equiv \sqrt{\frac{3}{2}\frac{\xi\Lambda^2}{M_p}}\,, \quad V_{\rm inf} = \frac{3}{4}\mu_{\rm inf}^2 M_p^2$$

- When we include the dynamics of the radius of φ, it becomes complicated, but still it works
- Parameter example:

$$\Lambda_{\not{C}\not{P}} = 3\times 10^{16}\,{\rm GeV}\,,$$
$$v_\varphi = 10^{15}\,{\rm GeV}\,,$$
$$\epsilon_\theta \simeq 2\times 10^{-3}\,,$$
$$\lambda_\phi = 5\times 10^{-11}\,,$$
$$\lambda_h\left(V_{\rm inf}^{1/4}\right) \simeq 0.07\,,$$
$$\kappa = 4\times 10^{-6}\,,$$
$$\xi \simeq 1.2\times 10^{4}\,,$$
$$\zeta = 80\,,$$
$$n = 4\,, \qquad \dot{\theta} \sim (n/2)\mu_{\rm inf}$$

corresponds to →

$$\mu_{\rm inf} = 3\times 10^{13}\,{\rm GeV}\,,$$
$$m_\theta \simeq 6\times 10^{13}\,{\rm GeV}\,,$$
$$m_\varphi = 10^{10}\,{\rm GeV}\,,$$
$$T_{\rm reh} \simeq 2.7\times 10^{13}\,{\rm GeV}$$

$$\frac{\eta_B}{\eta_B^{\rm obs}} \approx 3\times 10^{6}$$

Summary

Propose a model that entails a minimal addition to the Standard Model to simultaneously ensure

1. Higgs vacuum stability up to the Planck scale
   ↓ then
   Successful inflation
2. Leptogenesis via the pendulum mechanism
3. Generate the active neutrino masses