Spontaneous Leptogenesis
in
Higgs Inflation

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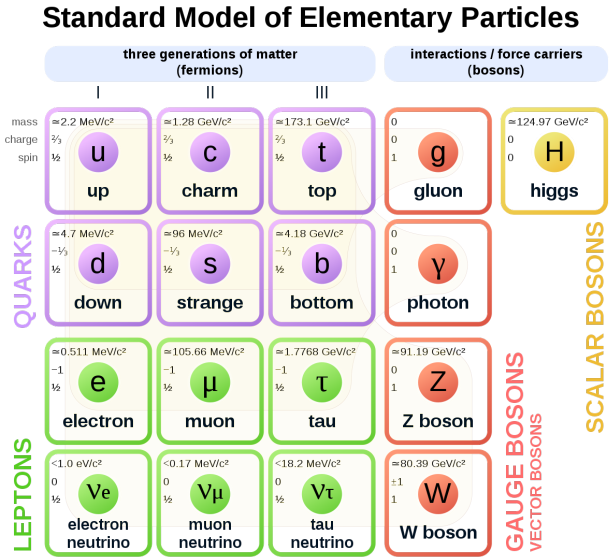
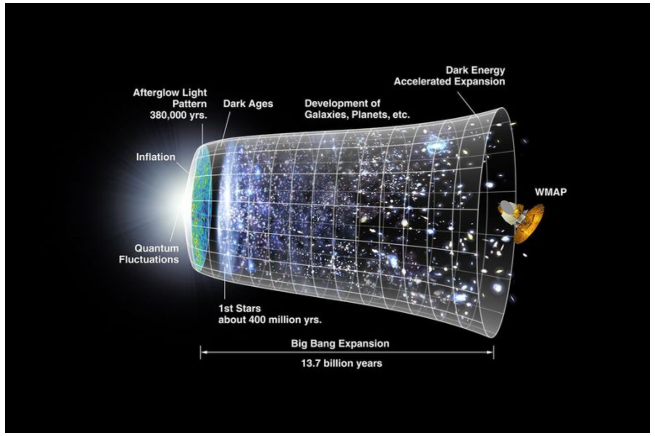
based on **arXiv:2010.07563**
In collaboration with Kin-ya Oda (Tokyo Woman's Christian U.), Seong Chan Park (Yonsei U.)

Introduction

- In Particle Physics : Standard Model
    - Dark Matter / Dark Energy
    - Baryon Asymmetry
        - $\eta_B \equiv \frac{n_B}{n_\gamma} \simeq (6.12 \pm 0.04) \times 10^{-9}$ (from BBN&CMB)
        - Cannot be explained within SM



- In Cosmology : Inflationary Paradigm
    - What is inflaton? SM Higgs?
    - How was universe thermalized? (Reheating)



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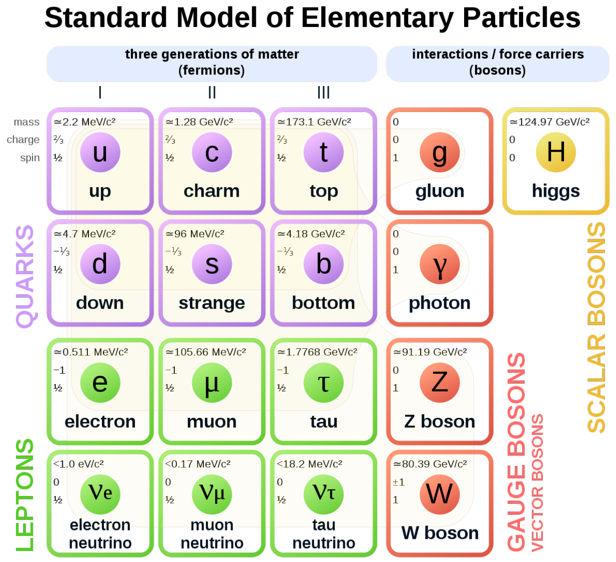

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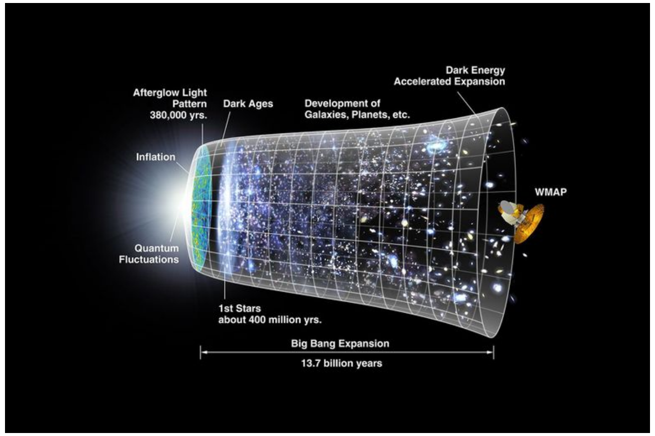


Higgs Inflation

- Model

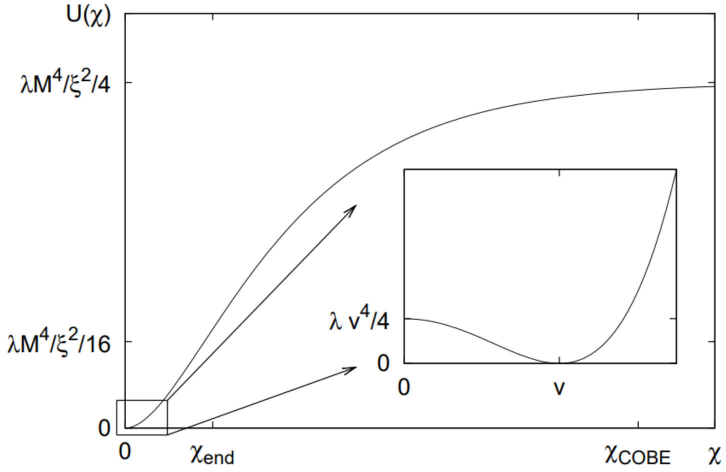
$$S_{J,\text{inf}} = \int d^4x\sqrt{-g_J}\left[\frac{1}{2}\left(M_P^2 + \boxed{\xi\phi_J^\dagger\phi_J}\right)R_J - \frac{1}{2}|\partial_\mu\phi_J|^2 - V_J(\phi_J)\right] \qquad V_J(\phi_J) = \frac{\lambda}{4}\phi_J^4$$

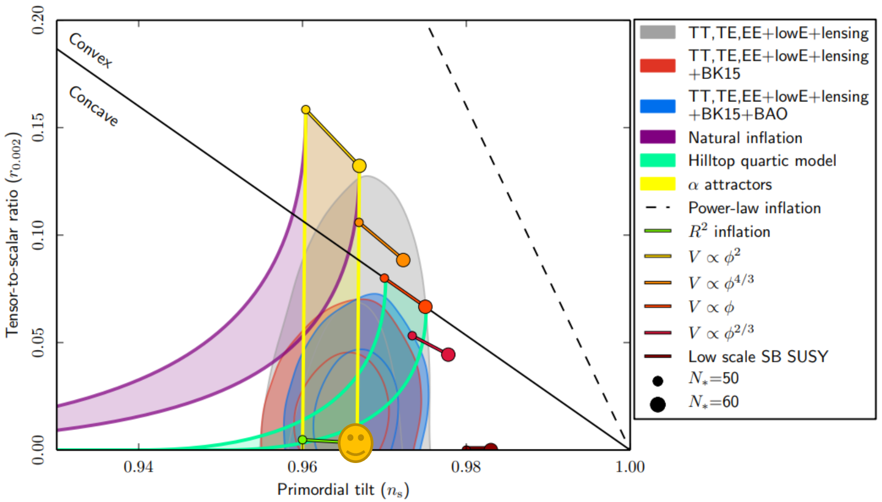
$$g_{\mu\nu} = \Omega(\phi_J)^2 g_{J\mu\nu} \Big\downarrow \ \Omega(\phi_J)^2 \equiv 1 + \frac{\xi}{M_P^2}\phi_J^2$$

$$\boxed{S_{E,\text{inf}} = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}|\partial_\mu\phi|^2 - V(\phi)\right]}$$

[F.L. Bezrukov *et al.* 0710.3755]

- Minimal (only candidate in SM) / Best-fit to Planck result

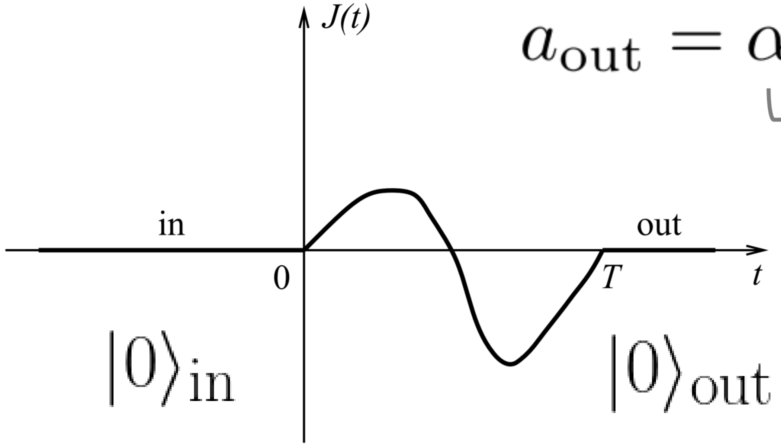




Particle Production & Reheating

- Higgs inflation : time dependent fermion masses ⇒ **Particle Production**

- *Non-perturbative* Particle Creation
    - When *adiabaticity conditions* are violated, the definition of the vacuum changes



$$a_{\rm out} = \underbrace{\alpha a_{\rm in} + \beta a^\dagger_{\rm in}}_{\textbf{Bogoliubov coefficients}}$$

$$N_i = \langle 0|a^\dagger_{\rm in} a^\dagger_{\rm in}|0\rangle_{\rm in} = 0$$

$$\downarrow$$

$$N_f = \langle 0|a^\dagger_{\rm out} a^\dagger_{\rm out}|0\rangle_{\rm in} = \underset{\textbf{Particle Production}}{\underline{|\beta|^2 \neq 0}}$$

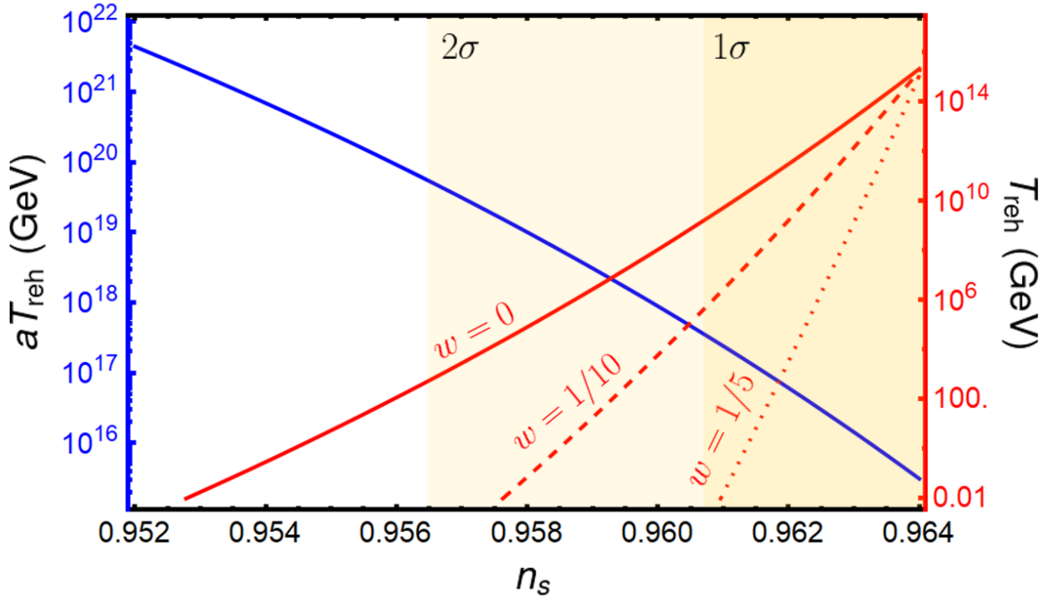
[F.L. Bezrukov *et al.* 0710.3755,
Juan Garcia-Bellido *et al.* 0812.4624
Yohei Ema *et al.* 1609.05209
Yuta Hamada *et al.* 2007.04701]

Reheating Temperature and Spectral Index

- Determining exact reheating temperature is very non-trivial.
- There exists a *consistency relation* between $\tilde{T} = a_{reh}T_{reh}$ and n_s

$$a_{\rm reh}T_{\rm reh} = \left(\frac{43}{11g(T_{\rm reh})}\right)^{\frac{1}{3}}\left(\frac{a_0T_0}{k_*}\right)H_ke^{-N_e}$$

[Jessica L. Cook *et al.* 1502.04673]



- For Higgs Inflation,

$$N_e = \frac{2}{1-n_s} \qquad H_k = \pi M_P\sqrt{\frac{3}{2}A_s(1-n_s)}$$

- Favored Regime $10^{15}{\rm GeV} \lesssim \tilde{T} \lesssim 10^{18}{\rm GeV}$

Higher Dimension Operators : Dim-5

- SM as EFT
    - On inflation, this is an important issue (cf. eta problem)
    - Here, we will consider *Planck-suppressed, symmetry breaking* operators
    - Can be considered as minimal / intrinsic amount of lepton asymmetry

- Dim-5 Operator : Weinberg Operator

$$\mathcal{L}_{\text{dim-5}} = \frac{c_5}{M_P}(\overline{L}\tilde{\Phi})(\tilde{\Phi}L)^\dagger \qquad \tilde{\Phi} \equiv i\sigma_2\Phi^*$$

    - Lepton number violation

Higher Dimension Operators : Dim-6

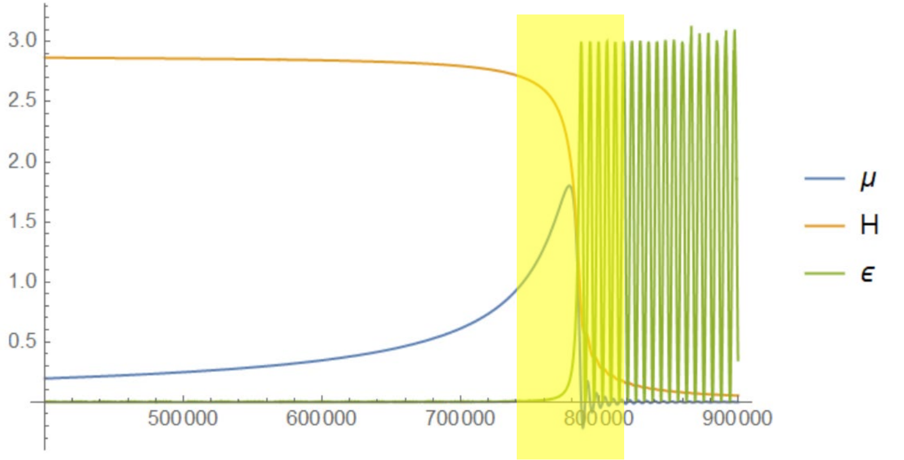
- Dim-6 Operator [Pearce *et al.* 1410.0722, 1505.02461]

$$\mathcal{O}_6 = -\frac{c_6}{M_P^2}\Phi_J^\dagger\Phi_J\partial_\mu j_L^\mu = \frac{c_6}{M_P^2}(\partial_\mu\phi_J^2)j_L^\mu = \underbrace{\frac{c_6}{M_P^2}(\partial_t\phi_J^2)}_{}j_L^0$$

Coherent field *spontaneously* breaks Lorentz symmetry

Coefficient of number density: effective chemical potential

- Large chemical potential during reheating
- *No wash-out* at late times



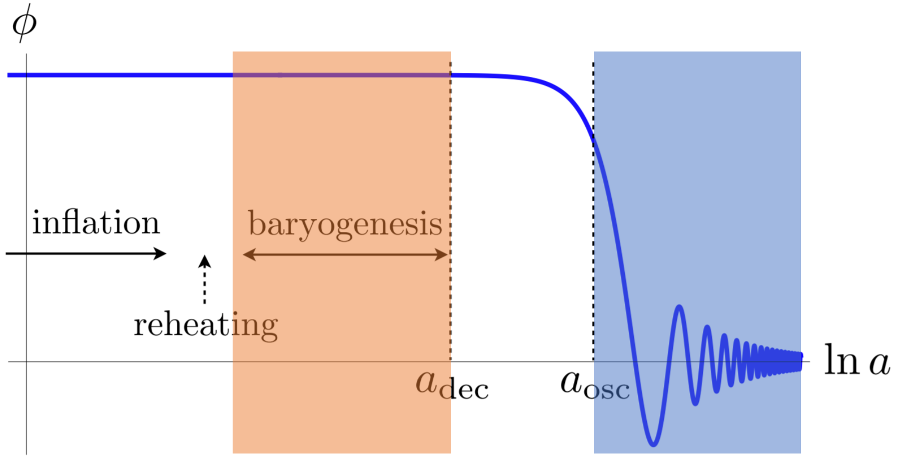
Spontaneous Baryogenesis

- Spontaneous Baryogenesis [A. G. Cohen and D. B. Kaplan (1987)]
  - Hot regime : Thermal Equilibrium $n_B - n_{\bar{B}} \simeq \frac{g}{6}\mu T^2$
  - Super-cooled regime : Perturbative/Non-perturbative Decay [A. Dolgov *et al.* hepph/9610405]
    - Possible scenario using SM Higgs was first considered by Kusenko *et al.* [1410.0722, 1505.02461]

(Spatially homogeneous)
Goldstone Boson

$$\frac{1}{\Lambda}(\partial_\mu \overset{\downarrow}{\phi}) j_B^\mu = \underset{\uparrow}{\frac{\dot{\phi}}{\Lambda}}(n_B - n_{\bar{B}})$$

Effective chemical potential μ



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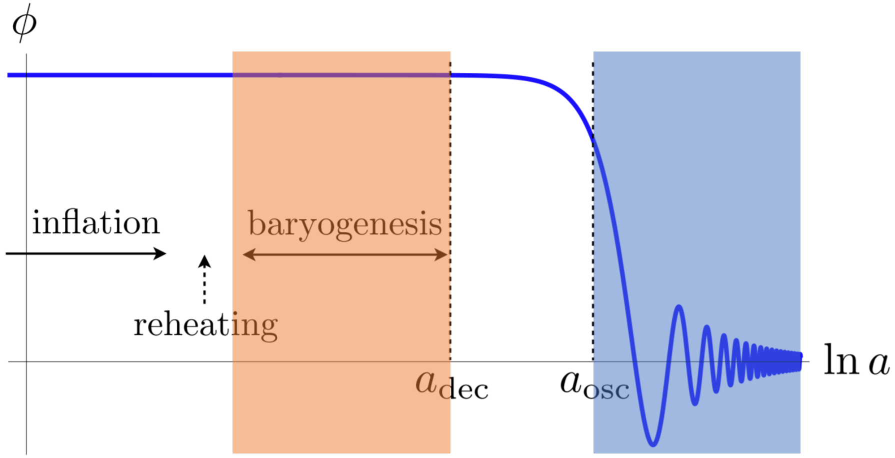


Also realized during the reheating

Neutrino Production

- Bogoliubov Transformation
  - Particle production (Neutrino) from time dependent classical background (Higgs)

$$(i\partial_\tau + \vec{\sigma}\cdot\vec{k})\nu_L = -\widetilde{m}_\nu (i\sigma_2)\nu_L^* - \widetilde{\mu}\nu_L$$

$$\alpha_s'(\tau,k) = -\frac{\beta_s(\tau,k)}{2\omega_s^2}\left[\widetilde{m}_\nu\widetilde{\mu}' - (sk+\widetilde{\mu})\widetilde{m}_\nu'\right] e^{2i\int_0^\tau \omega_s(\tau')d\tau'}$$

$$\beta_s'(\tau,k) = \frac{\alpha_s(\tau,k)}{2\omega_s^2}\left[\widetilde{m}_\nu\widetilde{\mu}' - (sk+\widetilde{\mu})\widetilde{m}_\nu'\right] e^{-2i\int_0^\tau \omega_s(\tau')d\tau'}$$

$$\alpha_s(0,k) = 1 \text{ and } \beta_s(0,k) = 0$$

- Manifest helicity dependence
- Time dependence of neutrino mass is essential

$$n_s(t) = \frac{1}{(a(t)/a_{\text{end}})^3}\int \frac{d^3k}{(2\pi)^3}|\beta_s(\tau(t),k)|^2$$

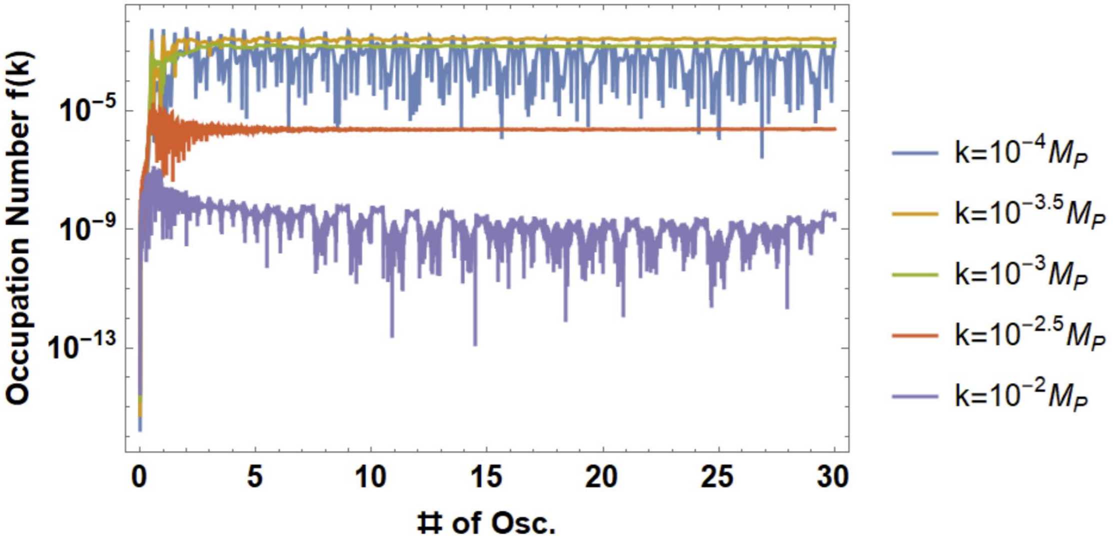
$\uparrow$

occupation number $f_s(t,k)$

$$\eta_L(t_{\text{reh}}) \equiv \left.\frac{n_L}{n_\gamma}\right|_{\text{reh}} = \frac{\pi^2}{2\zeta(3)}\left.\frac{\widetilde{n}_L}{\widetilde{T}^3}\right|_{\text{reh}}$$

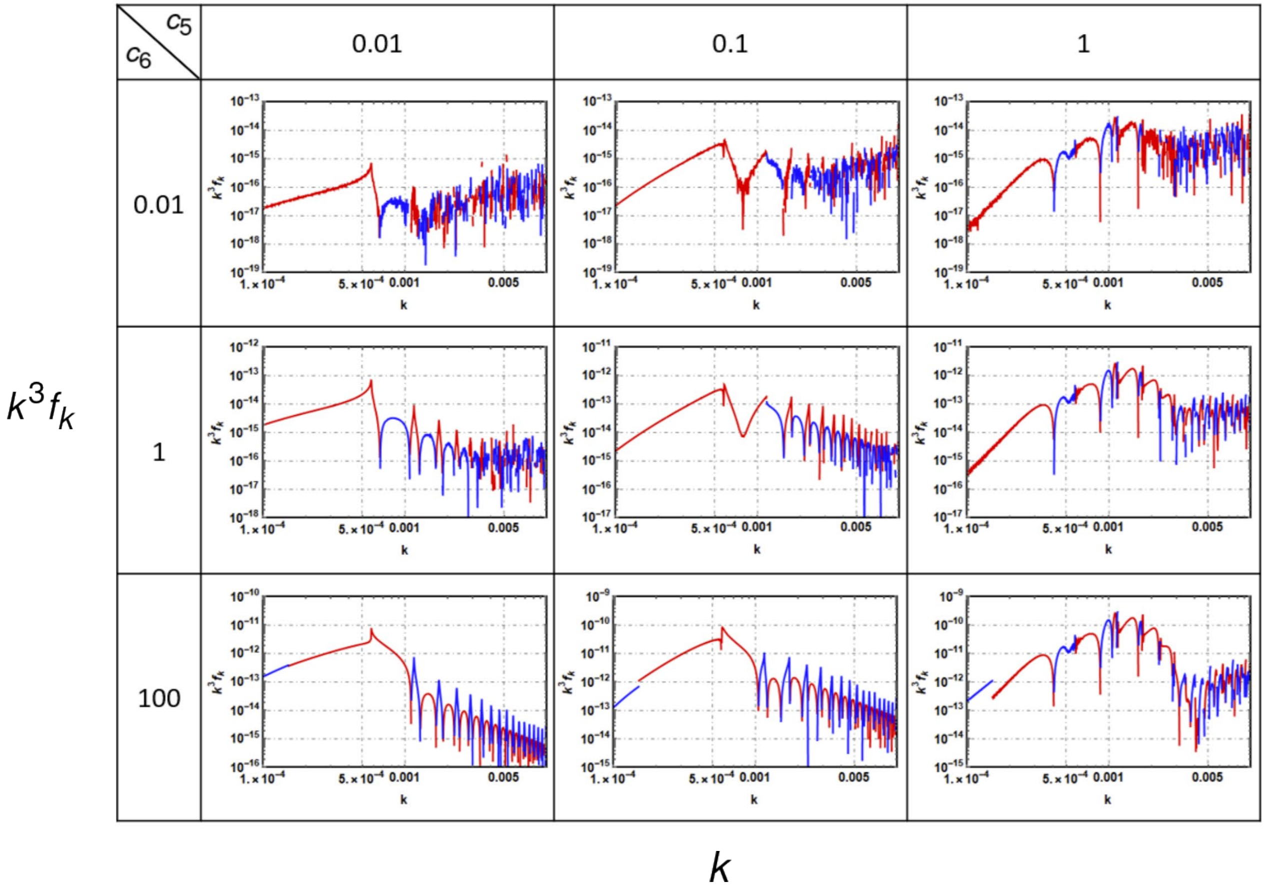
- transforms to B asymmetry via sphaleron

Lepton Asymmetry



- Almost produced at early time (≤ 5 osc.)
  → Insensitive to reheating history

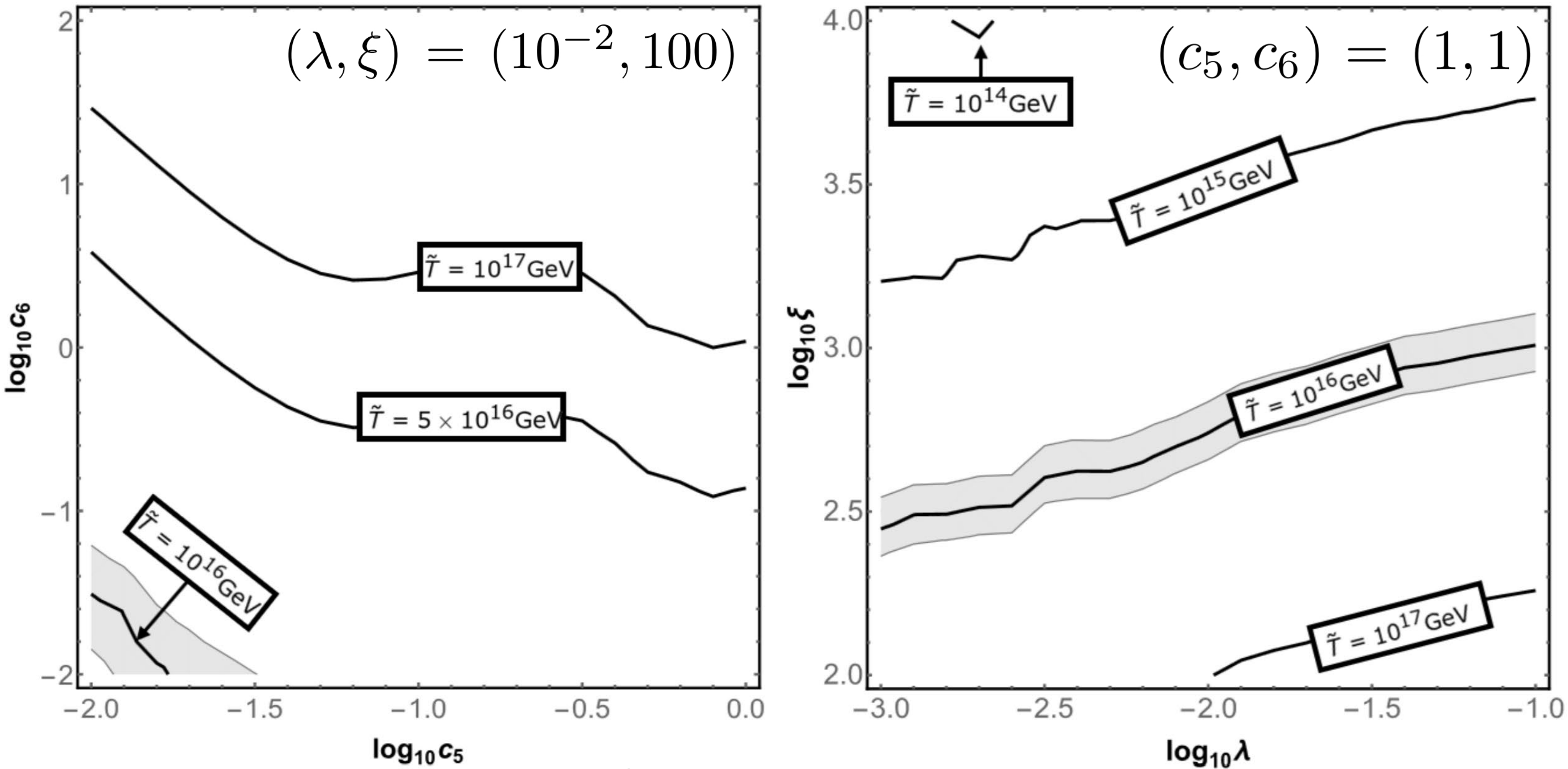
- Large momentum mode are suppressed.



[**SML**, K. Oda, SC. Park. 2010.07563]

Results

$$\eta_B(c_5, c_6, \widetilde{T}) \simeq \frac{C_{\rm sphal}^{\rm (SM)} \pi^2 \widetilde{n}_L}{2\zeta(3)\widetilde{T}^3}$$



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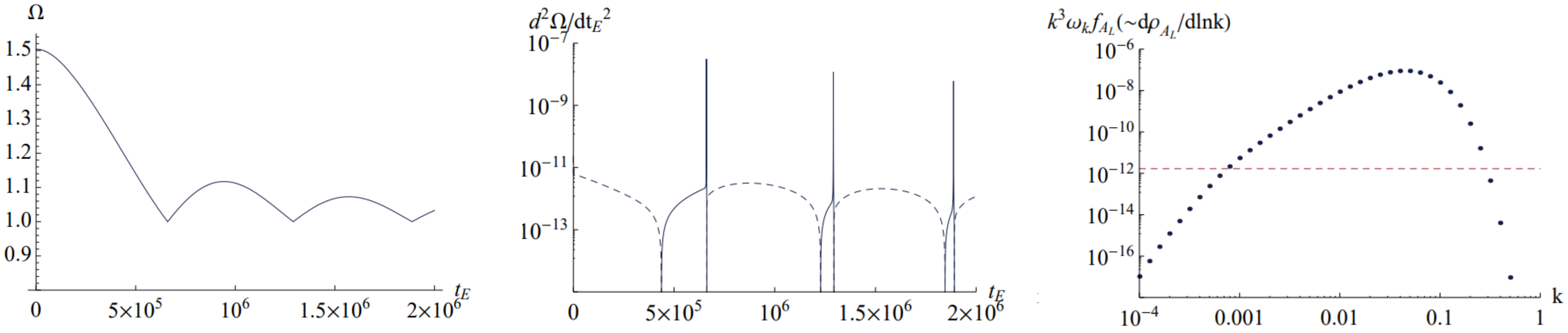
Conclusion

- We calculated intrinsic amount of the baryon asymmetry from Higgs inflation, in the EFT point of view.
  - Planck suppressed / symmetry breaking operators (no explicit CP violation)
- This is also applicable for other inflation models
  - With time dependent neutrino masses
- In single field model, minimal asymmetry already explains current observation with high reheating temperature
  - favored high temperature range : $10^{15}\mathrm{GeV} \lesssim \widetilde{T} \lesssim 10^{18}\mathrm{GeV}$

Back Up : Unitarity Problem

- Longitudinal gauge boson decays are non-trivial [Yohei Ema *et al.* 1609.05209]
    - Inflaton lose its energy during the zero crossing

$$m_{A_L}^2 = m_A^2 - \frac{k^2}{k^2+m_A^2}\left(\frac{m_A''}{m_A} - \frac{3m_A'^2}{k^2+m_A^2}\right)$$



- Issues
    - Unitarity Problem $k \sim \sqrt{\lambda} M_P \gg \frac{M_P}{\xi}$
    - Higher operator dependence :
        - Reheating cannot be determined by low E theory

[Yuta Hamada *et al.* 2007.04701]