SPONTANEOUS LEPTOGENESIS IN HIGGS INFLATION

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based on **arXiv:2010.07563**

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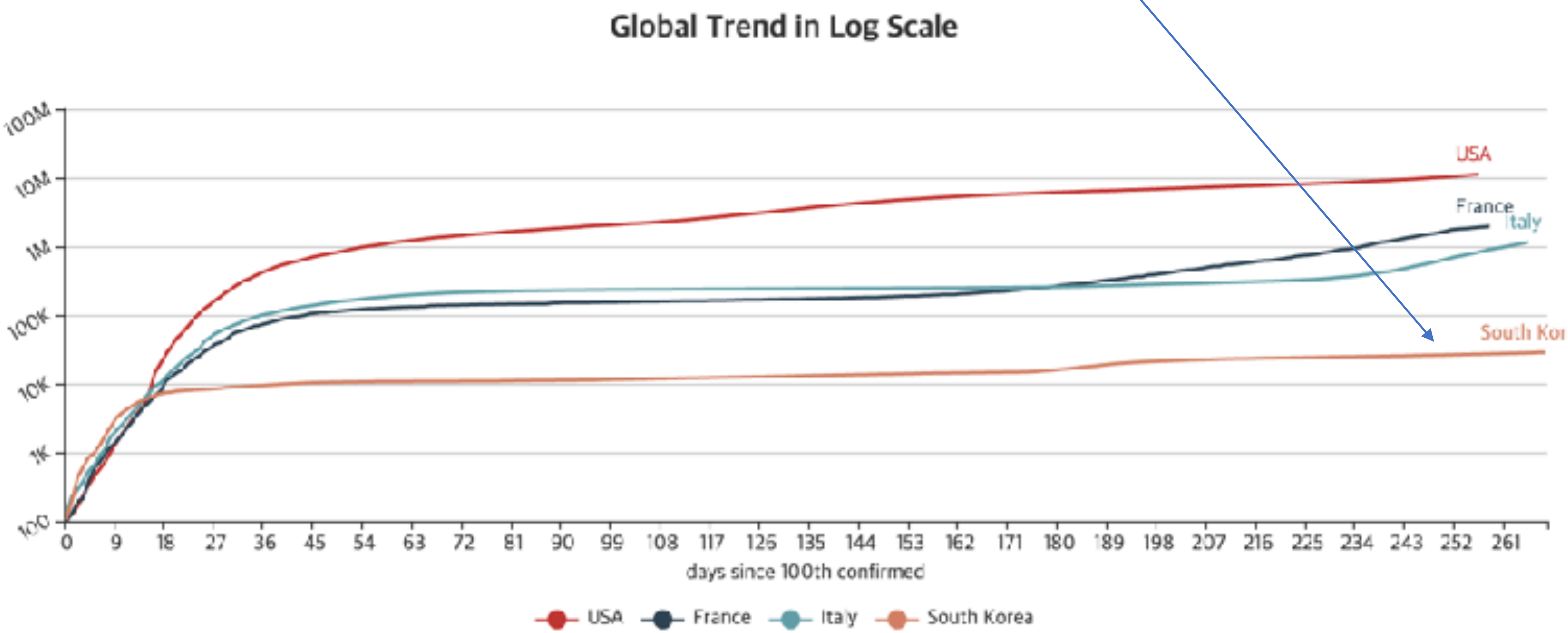
If something works well,
there could be some good reasons behind



'Higgs' works well beyond the original expectation

- EW symmetry breaking
- Masses of elementary particles
- Successful inflation BEST fitting the data

Bezrukov, Shaposhnikov 0710.3755

Hamada, Kawai, Oda, SCP 1403.5043, 1408.4864 (Critical)

- Dark matter can be understood by Primordial Black Hole production

Cheong, Lee, SCP 1912.12032

- Baryon asymmetry of the universe ==> THIS TALK

Lee, Oda, SCP 2010.07563

Content

- Review on Baryon Asymmetry, Higgs Inflation & Reheating
- Higher Dimensional Operators (Dim 5, Dim 6) for LNV & chemical potential for baryon-number
- Leptogenesis in Higgs inflation
- Conclusions

Introduction

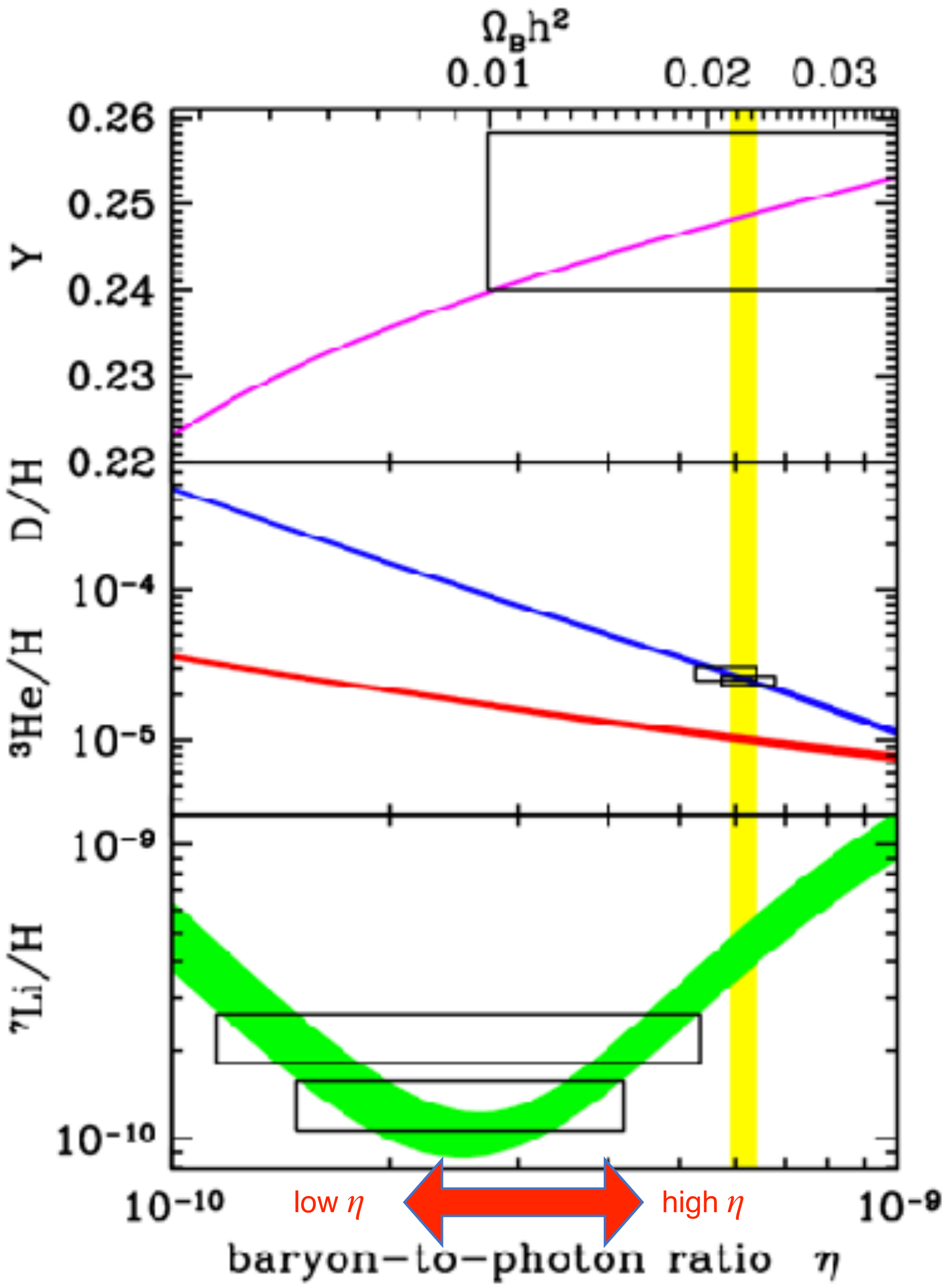
- We see baryons rather than anti-baryons in nature

$$\frac{\bar{p}}{p} \sim 10^{-4} \text{ in cosmic ray}$$

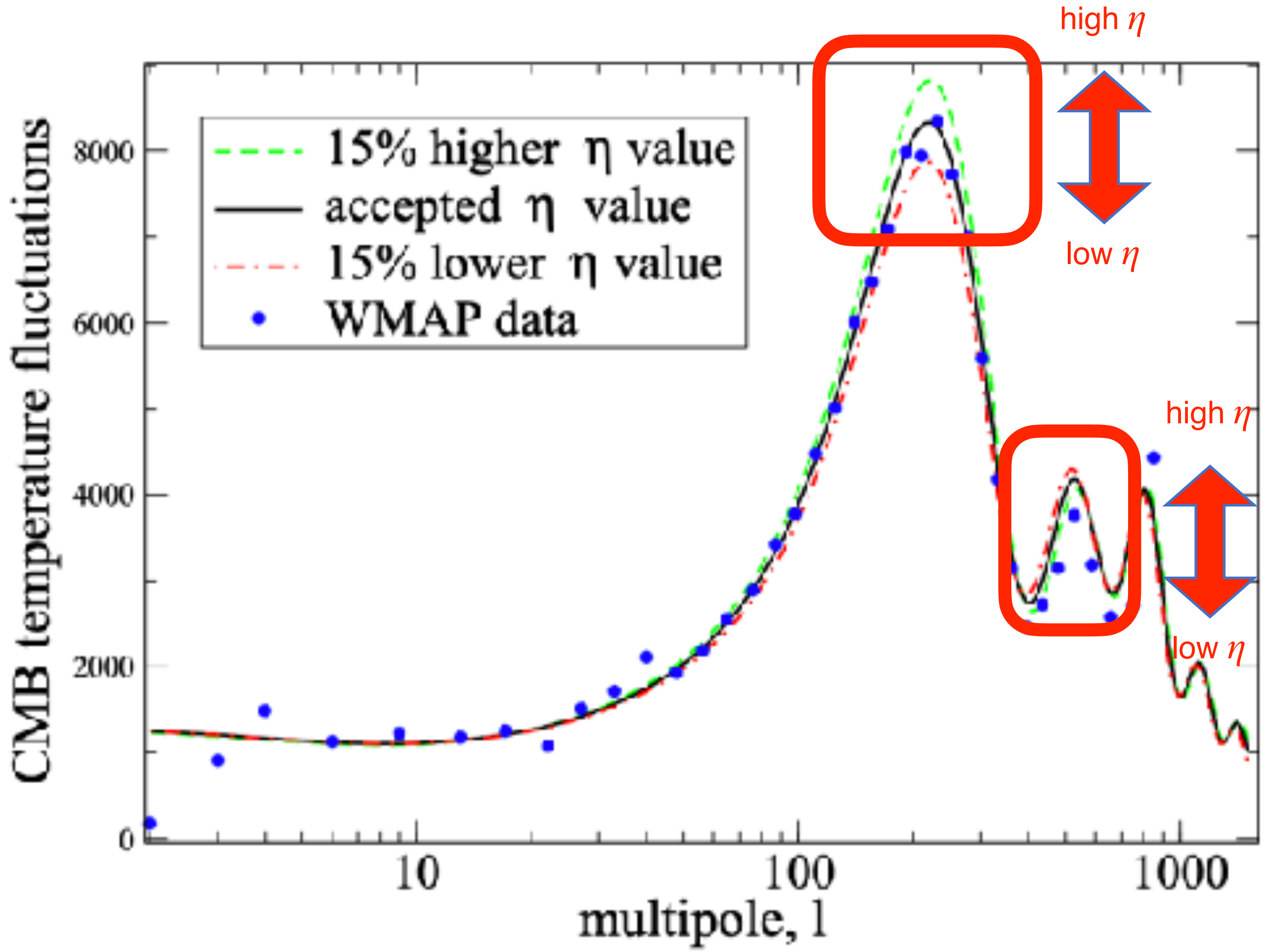
- Making $e^+, \bar{p}$ cost a lot at colliders
- Baryon asymmetry is well determined by BBN & CMB measurements

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

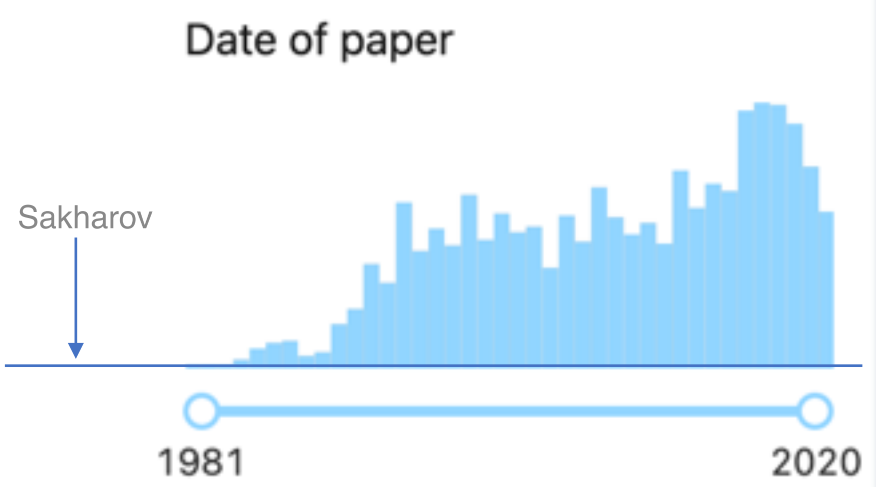
  - n_B : number density of Baryons
  - $n_{\bar{B}}$: number density of anti-Baryons
  - n_γ : number density of photons $= \frac{\zeta(3)}{\pi^2} g_* T^3$, $g_* = 2$ polarizations, $\zeta(3) = 1.20\cdots$



Baryon asymmetry from CMB spectrum



Questions

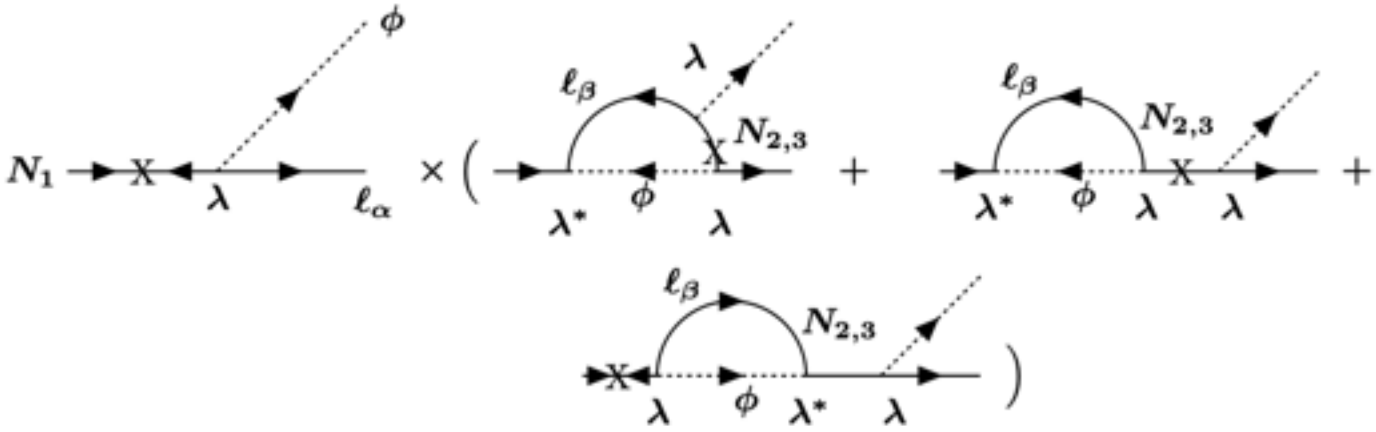


- B and anti-B are spatially separated? ==> no
- Is it generated before the inflation? ==> no
- **Why is it non-zero? ==> Baryogenesis**
- With exact CPT symmetry, **Sakharov's 3 conditions (1967)** are needed
  - B-violation, C & CP violation, out of thermal equilibrium
- Then enormous efforts have been made in 'Baryogenesis' ever since
- **Leptogenesis** is my personal favorite …

Leptogenesis

M. Fukugita, T. Yanagida (1986)

- Thanks to the sphaleron process active Q>EW, the generated lepton number can be converted into baryon number
- Lepton number can be generated in heavy Majornana Neutrino decay



- A beautiful idea but hardly tested : $m_N \sim m_{\text{GUT}}$

We claim

In Higgs inflation, **spontaneous Leptogenesis** can be still achieved with help from Weinberg operator (Dim-5) and chemical potential of lepton number (Dim-6) with no new particle

Higgs Inflation

Non-minimal coupling

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

- Model

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

Weyl transformation

$$g_{\mu\nu} = \Omega(\phi_J)^2 g_{J\mu\nu} \qquad \Omega(\phi_J)^2 \equiv 1 + \frac{\xi}{M_P^2}\phi_J^2 \qquad \psi_J \to \Omega^{Dim}\psi$$

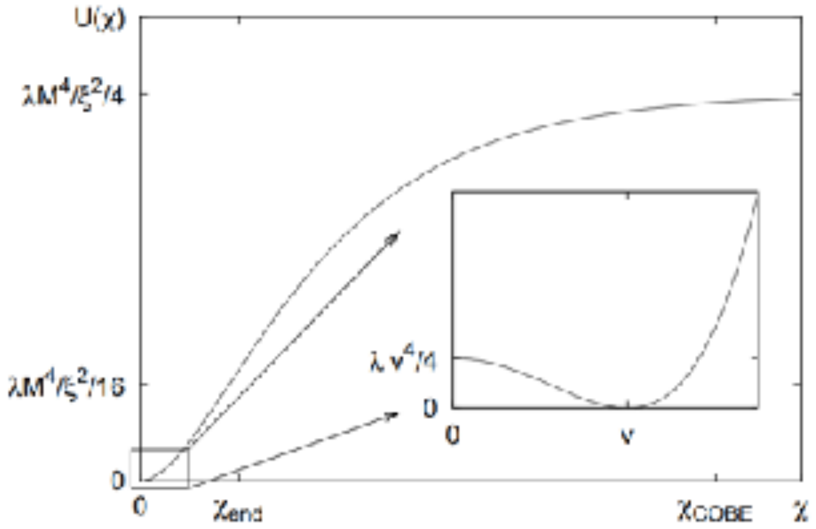
Dim : conformal dimension

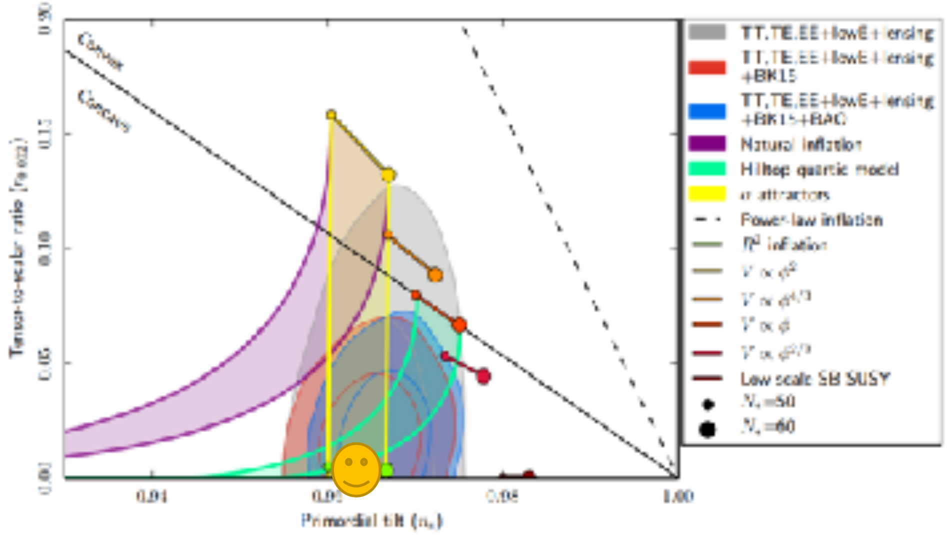
$3/2$: *fermion*

1 : *boson*

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

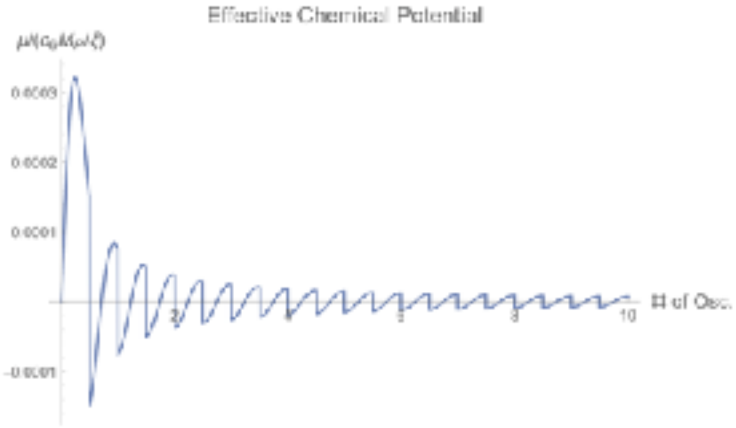
- Minimal (only candidate in SM) / Best-fit to Planck result

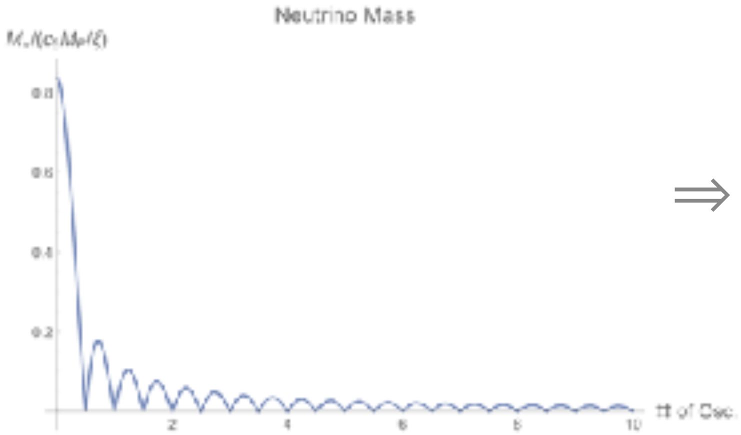




Matter production in Higgs inflation

- Time Dependent Fermion Masses from $\sqrt{g}yH\bar{\psi}\psi$ and $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$
- Scaling behavior & dynamics of Higgs : $m \to \dfrac{m}{\Omega(t)}$
- 'Change of mass' can be understood as change of vacuum
  ==> **Bogoliubov transformation** ==> **Particle Production** (just as Hawking Radiation!)





$\Rightarrow$ **Particle Production**

Higher Dimension Operators : Dim-5

- SM as EFT
- 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
  - CP violation

  - Possible Origin : Heavy Majorana Neutrino $M_N \sim 10^{15}\ \text{GeV}$
    - Note that the reheating temperature $T_{\text{rch}} < 10^{15}\ \text{GeV}$

Higher Dimension Operators : Dim-6

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

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

- Coherent Field spontaneously breaks CPT

- Chemical Potential of lepton number
  ==> Energy costs differently from anti-lepton to lepton

- Dominantly acting ONLY at reheating when time derivative becomes sizable
  (cf) During inflation, inflaton slowly rolling

Neutrino masses are derived from the Weinberg operator

$$\sqrt{-g_J}\frac{c_5}{M_P}\phi_J^2\psi_J\psi_J = \sqrt{-g}\frac{c_5}{M_P}\frac{\phi_J^2}{\Omega}\psi\psi. \quad (A.21)$$

with identification $y^2/M_N = c_5/M_P$.

Neutrino masses from seesaw:

$$S_f = \int d^4x\sqrt{-g_J}\left[-\frac{1}{2}\overline{\psi}_J e_{Ja}{}^{\mu}\gamma^a D_{J\mu}\psi_J - \frac{1}{2}(M_N + y\phi_J)\overline{\psi}_J\psi_J + \frac{c}{\Lambda^2}\left(\partial_\mu\phi_J^2\right) J^\mu_{JL}\right]$$

Note that the Dirac and Majorana mass terms change differently as

$$M_N \to \frac{M_N}{\Omega} = M_N e^{-\frac{1}{\sqrt{6}}\frac{|\phi|}{M_P}}, \qquad M_D \to \frac{y}{\Omega}\phi_J = \frac{yM_P}{\sqrt{\xi}}\left(1 - e^{-\sqrt{\frac{2}{3}}\frac{|\phi|}{M_P}}\right)^{1/2}.$$

If the origin of neutrino masses is the seesaw mechanism,

$$m_\nu = \frac{M_D^2}{M_N} \to \frac{y^2\phi_J^2}{M_N\Omega} = \frac{2y^2M_P^2}{M_N\xi}\sinh\left(\frac{|\phi|}{\sqrt{6}}\right).$$

Particle Production in curved spacetime

- Bogoliubov Transformation
  - When *adiabaticity conditions* are violated, the definition of the vacuum changes
  - Non-zero β coefficient is interpreted as *particle production*
  - Particle production (Neutrino) from time dependent classical background (Higgs)

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

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

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

- Manifest helicity dependence $\quad \alpha_s(0,k) = 1$ and $\beta_s(0,k) = 0$
- Time dependence of neutrino mass is also essential

occupation number $f_s(t,k)$

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

$$n_L|_{\text{reh}} \equiv \lim_{t\to t_{\text{reh}}} n_\ell(t) - n_{\bar{\ell}}(t)$$

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

- transforms to B asymmetry via sphaleron

little more detail … "standard technique" (see appendix)

$$\left\{a_s(\vec{k}), a^\dagger_{s'}(\vec{k}')\right\} = (2\pi)^3\delta_{ss'}\delta(\vec{k}-\vec{k}')$$

$$\nu_L = \int \frac{d^3k}{(2\pi)^3} \sum_{s=\pm 1} \left[\xi_s(\tau,\vec{k}) a_s(\vec{k}) e^{i\vec{k}\cdot\vec{x}} + \chi_s(\tau,\vec{k}) a^\dagger_s(\vec{k}) e^{-i\vec{k}\cdot\vec{x}}\right]$$

$$\xi_s(\tau,\vec{k}) = u_s(\tau,\vec{k}) h_s(\vec{k}), \qquad \chi^c_s(\tau,\vec{k}) = v_s(\tau,\vec{k}) h_s(\vec{k})$$

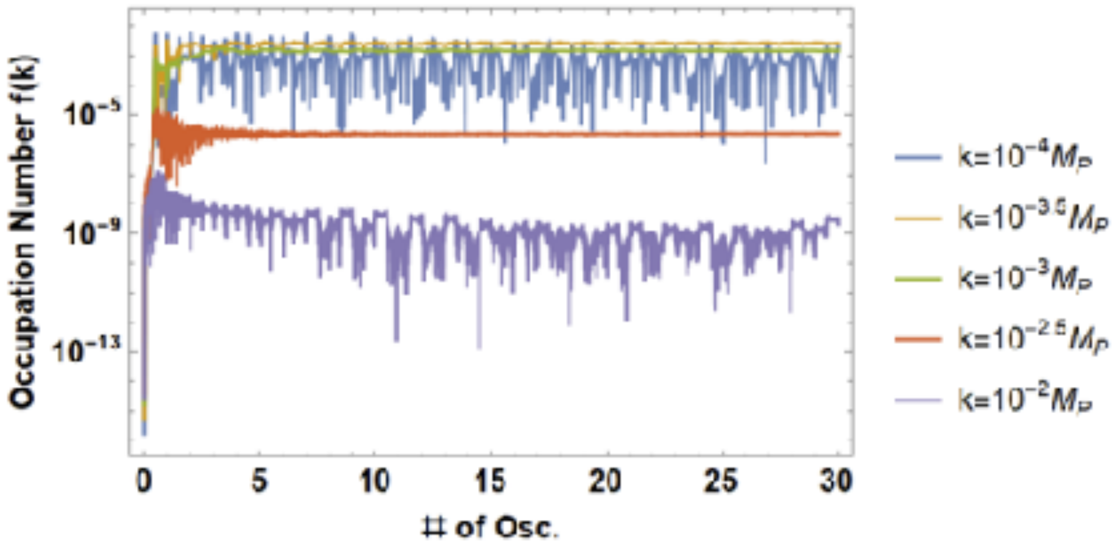
$$u_s(\tau,\vec{k}) = \frac{\alpha_s}{\sqrt{2}}\sqrt{1-f_s}\, e^{-i\int_0^\tau \omega_s(\tau')d\tau'} + \frac{\beta_s}{\sqrt{2}}\sqrt{1+f_s}\, e^{i\int_0^\tau \omega_s(\tau')d\tau'},$$

$$v_s(\tau,\vec{k}) = -\frac{\alpha_s}{\sqrt{2}}\sqrt{1+f_s}\, e^{-i\int_0^\tau \omega_s(\tau')d\tau'} + \frac{\beta_s}{\sqrt{2}}\sqrt{1-f_s}\, e^{i\int_0^\tau \omega_s(\tau')d\tau'},$$

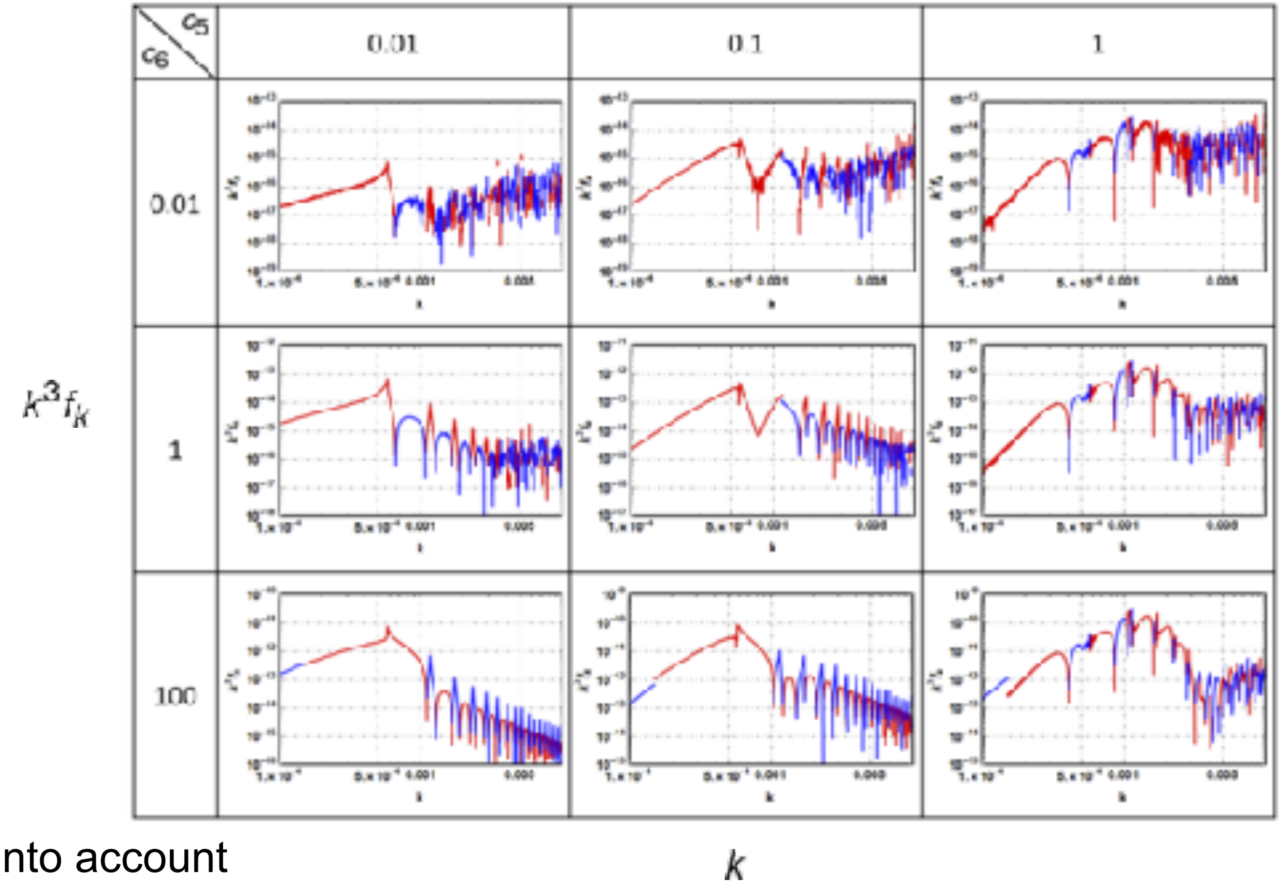
where

$$\omega_s^2(\tau,\vec{k}) = (k+s\tilde{\mu})^2 + \tilde{m}_\nu^2, \qquad f_s \equiv \frac{sk+\tilde{\mu}}{\omega_s}.$$

Lepton Asymmetry



Occupation number for particle, anti-particle



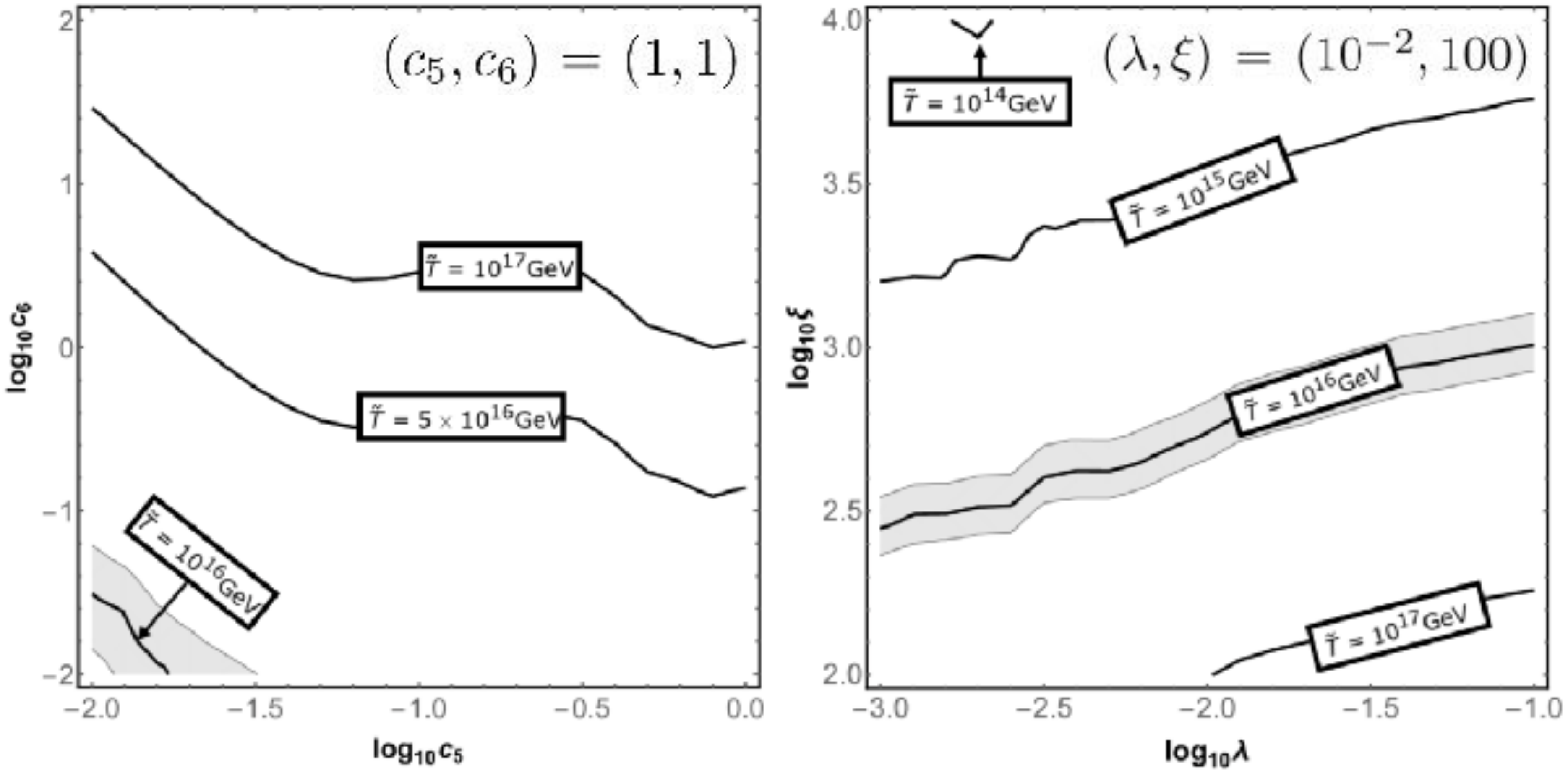
- Perform numerically taking actual inflationary dynamics into account
- It turned out that almost all asymmetry is produced at early time (≤ 5 osc.)

→ Insensitive to the details of late time reheating history

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

Results for observed B-asymmetry

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



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

Summary & Conclusion

- Coherently oscillating Inflaton field provide natural possibility of spontaneous baryogenesis during the reheating.
- With the help of Planck-suppressed higher dimension operators, Higgs inflation *consistently* explains baryon asymmetry with its unique characteristics (e.g. time dependent fermion masses), albeit large reheating temperature with $10^{15}\ \mathrm{GeV} \lesssim a T_{\mathrm{reh}} \lesssim 10^{18}\ \mathrm{GeV}$
- Future collider experiments (e.g. top quark mass) and astrophysical observations (e.g. spectral index) will provide direct/indirect probes to our scenario.