Leptogenesis in Higgs Inflation

Seong Chan Park

based on **arXiv:2010.07563**

with Sung Mook Lee (Yonsei), Kin-ya Oda (Osaka)

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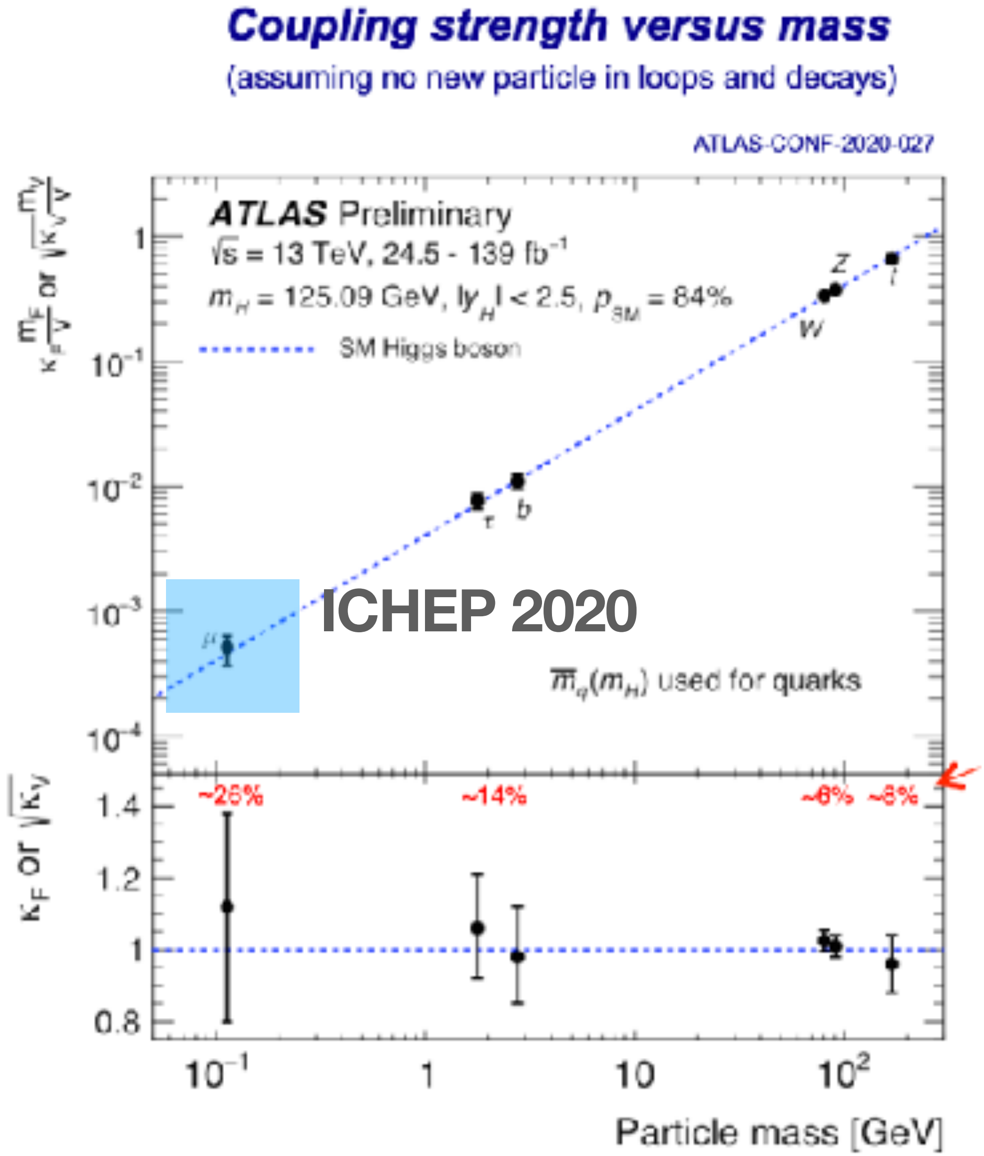
Higgs : much more profound than we thought

- Electroweak symmetry breaking (1965)
- Giving masses for elementary particles (1967)
- Inflation (1987, 1997, 2007, 2008, 2014)
- Reheating & Preheating (2015, 2018, 2019, 2020)
- Dark matter by PBH (2018,2019, 2020)
- **Leptogenesis (2020) ==> THIS TALK**



References

A rich phenomenology of Higgs inflation!

- Inflation by non-minimal coupling SCP, Yamaguchi JCAP (2008)
- Higgs Inflation is Alive Hamada, Kawaii, Oda, SCP, PRL 112, 241301 (2014)
- Higgs inflation from Standard model criticality Hamada, Kawaii, Oda, SCP, PRD 91, 053008 (2015)
- Clockwork for Higgs inflation SCP, Shin EPJC 79 (2019)
- Hillclimbing inflation in metric and Palatini formulations, Jinno, Kaneta, Oda, SCP, PLB791(2019)
- On the violent preheating in the mixed Higgs-R^2 model, He, Jinno, Kamada, SCP, Starobinsky, Yokoyama PLB791 (2019)
- Beyond the Starobinsky model for inflation, Cheong, Lee, SCP PLB805 (2020)
- Higgs inflation in metric and Palatini formalisms, Jinno, Kubota, Oda, SCP, JCAP 2003(2020)
- Higgs Inflation and the Refined dS Conjecture Cheong, Lee, SCP PLB 789 (2019)
- PBH in Higgs inflation, Cheong, Lee, SCP, JCAP (2020)
- **Leptogenesis in Higgs inflation, S. M. Lee, K-y. Oda, SCP (2020.07563) => THIS TALK**

Baryon number in universe

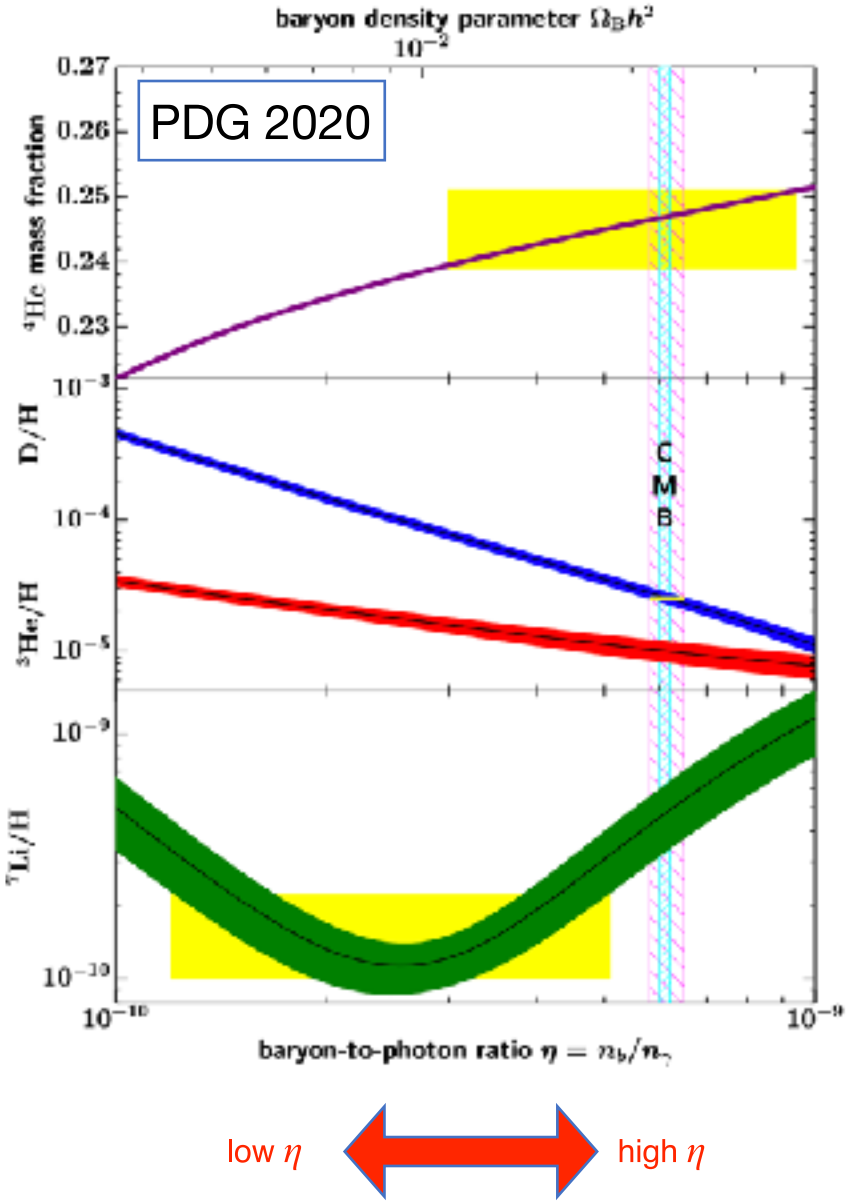
- We see baryons rather than anti-baryons in nature

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

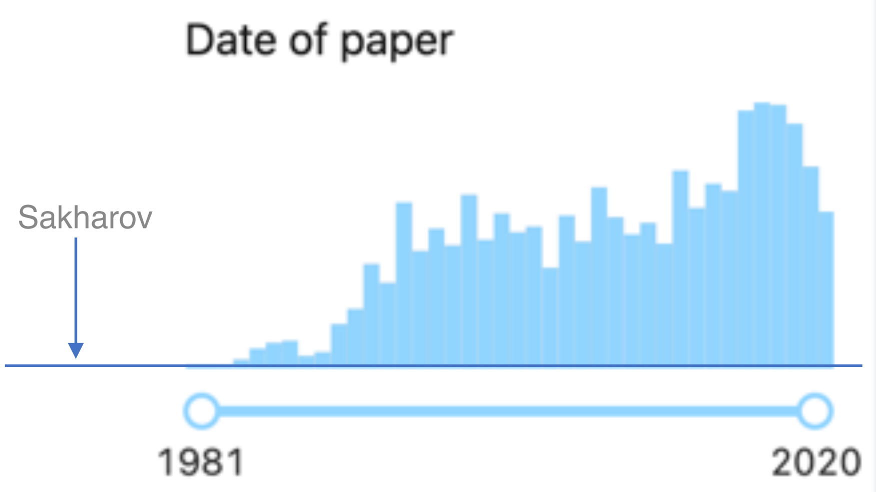
- Making anti-particles cost a lot at colliders
- Baryon asymmetry is well determined by BBN & CMB measurements

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

  - 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, $\zeta(3) = 1.20\cdots$



Some key issues



- 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
  - If CPT is spontaneously broken, B-violation, chemical potential for B-number (or L-number) are needed
- Thanks to sphaleron process in the SM, 'Leptogenesis' can work as well. (L -> B)

Fukugita, Yanagida (1986)

We claim

In Higgs inflation, spontaneous Leptogenesis can be achieved with no new particle beyond the SM but with help from effective operators

-Weinberg operator (Dim-5)

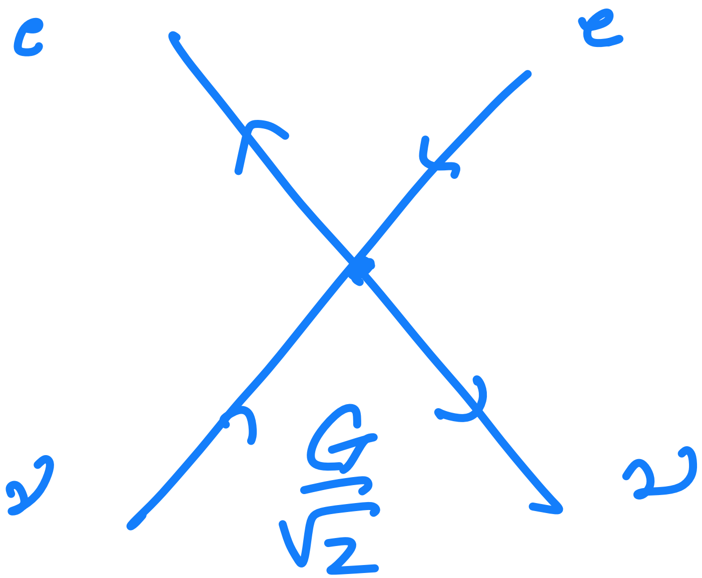
-Higgs-lepton current interaction (Dim-6)

The idea will be tested by collider experiments as well as cosmological, astrophysical observations.

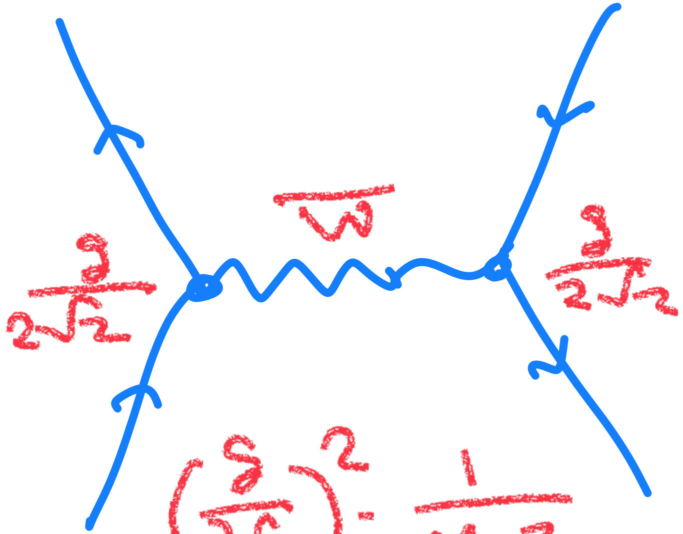
The Higgs in the SM

- $$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + G^0) \end{pmatrix} \sim \left(1, \frac{1}{2}, \frac{1}{2}\right)_{SM}$$
- $\mathscr{L}_{Higgs} = |D_\mu H|^2 - \lambda(|H|^2 - v^2/2)^2$: The most generic renormalizable action
- $v = 246.22\ \mathrm{GeV}$ determined from $G_F = \dfrac{1}{\sqrt{2}v}$ known from 70s
- $\lambda = \dfrac{m_h^2}{2v^2} = \dfrac{(125.35 \pm 0.12)^2}{2 \times 246.22^2} = 0.12959 \pm 0.00040 \approx \dfrac{1}{8}$ (LHC, 2012)

Vacuum expectation value



$\Leftarrow$



$G_F = 1.166\times 10^{-5}\ \mathrm{GeV}^{-2}$

$$\left(\frac{g}{2\sqrt{2}}\right)^2 \cdot \frac{1}{M_W^2} = \frac{g^2}{8M_W^2} = \frac{g^2}{8\cdot\left(\frac{1}{2}gv\right)^2} = \frac{1}{2v^2}$$

$$\therefore \frac{G}{\sqrt{2}} = \frac{1}{2v^2}$$

$$H = \begin{pmatrix} G^+ \\ \frac{v + h + G^0}{\sqrt{2}} \end{pmatrix}$$

G^+, G^0: Goldstone Bosons $\Rightarrow$ "eaten" by $W^\pm$, Z^0

v: VEV

h: physical Higgs

$$V = \lambda \left(|H|^2 - v^2/2\right)^2 , \quad |H|^2 = \frac{(v+h)^2}{2} \text{, unitary gauge}$$

$$= \lambda \left(\frac{h^2}{2} + vh\right)^2 = \frac{\lambda}{4} h^4 + \lambda v h^3 + \lambda v^2 h^2$$

$\frac{\lambda}{4} h^4$ ↑ λ_{hhhh}

$\lambda v h^3$ ↑ λ_{hhh}

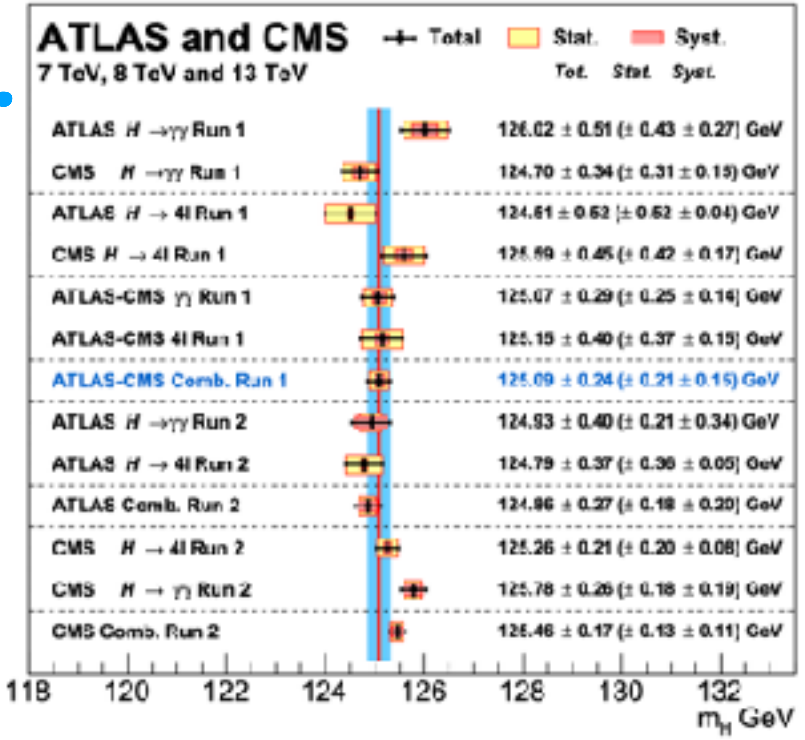
$\lambda v^2 h^2$ ↑ $\frac{1}{2} m_h^2$

The self coupling

$$\lambda = \frac{m_h^2}{2v^2} \quad \text{SM relation}$$

$$= \frac{(125\ \text{GeV})^2}{2 \times (246\ \text{GeV})^2}$$

$$\approx \frac{1}{8}$$



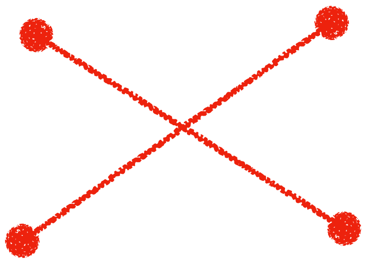
The SM Higgs potential

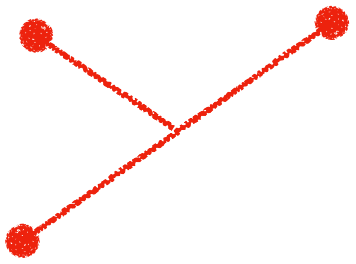
as determined by the SM & the LHC data

SM prediction

$$V(h) = \frac{1}{32} h^4 + \frac{(246\,\text{GeV})}{8} h^3 + \frac{1}{2} \cdot (125\,\text{GeV})^2 h^2$$

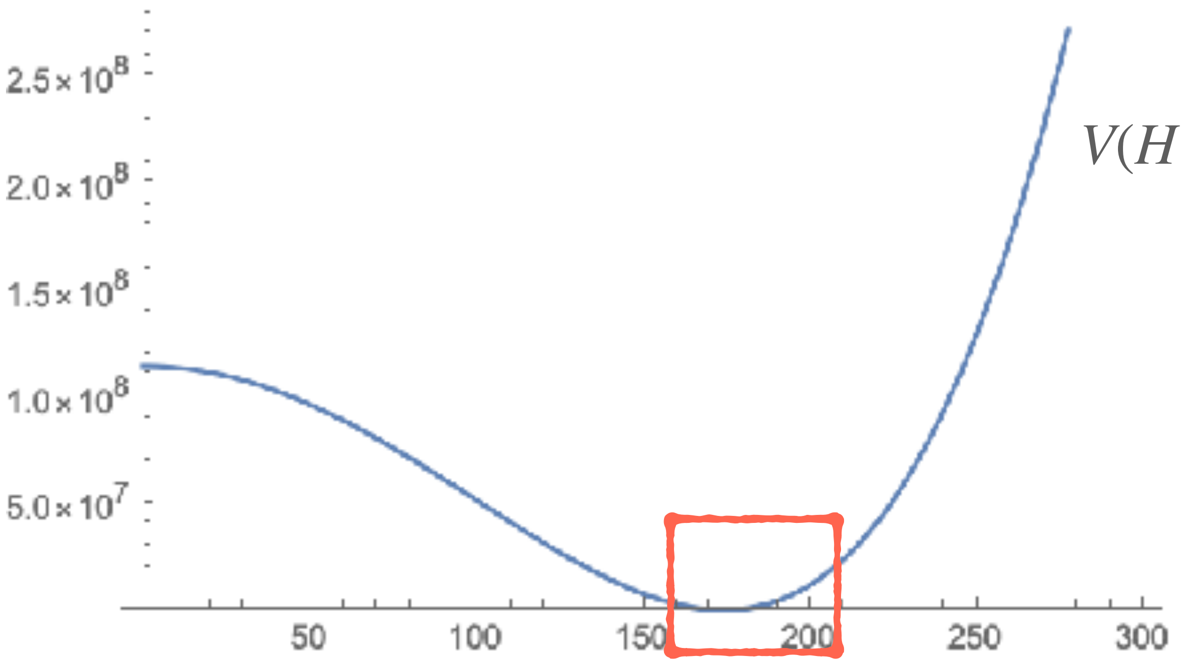
Quadruple | Triple | LHC





Look!

Quadruple, Triple couplings should be measured by Future collider experiments!



The SM prediction

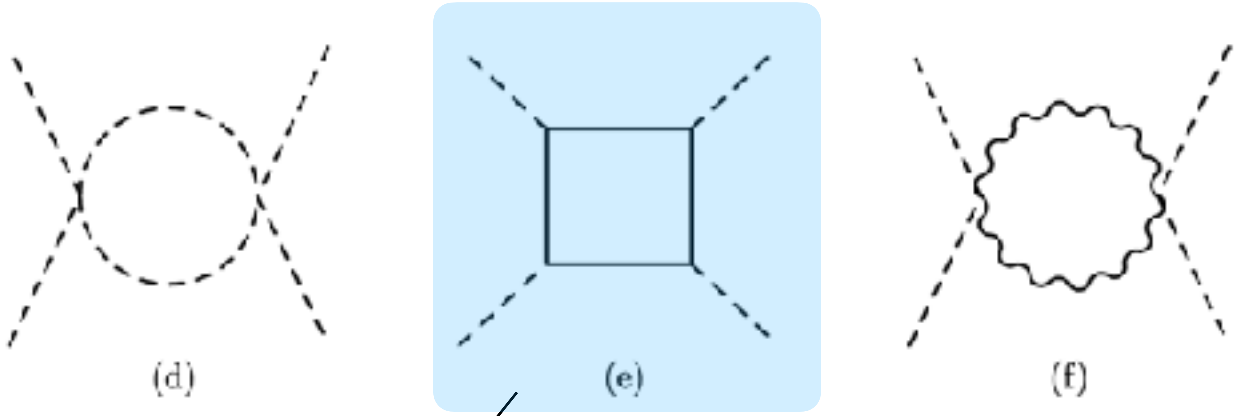
$$V(H) = \lambda(|H|^2 - v^2/2)^2$$

We only have seen this part!

$$V''(h) = m_h^2$$

Quantum Loop effects for Quadruple coupling

Simone, Hertzberg, Wilczek (PLB 2009), Hamada, Kawai, Oda, SCP (PRL 2014)



+ (2-loop)

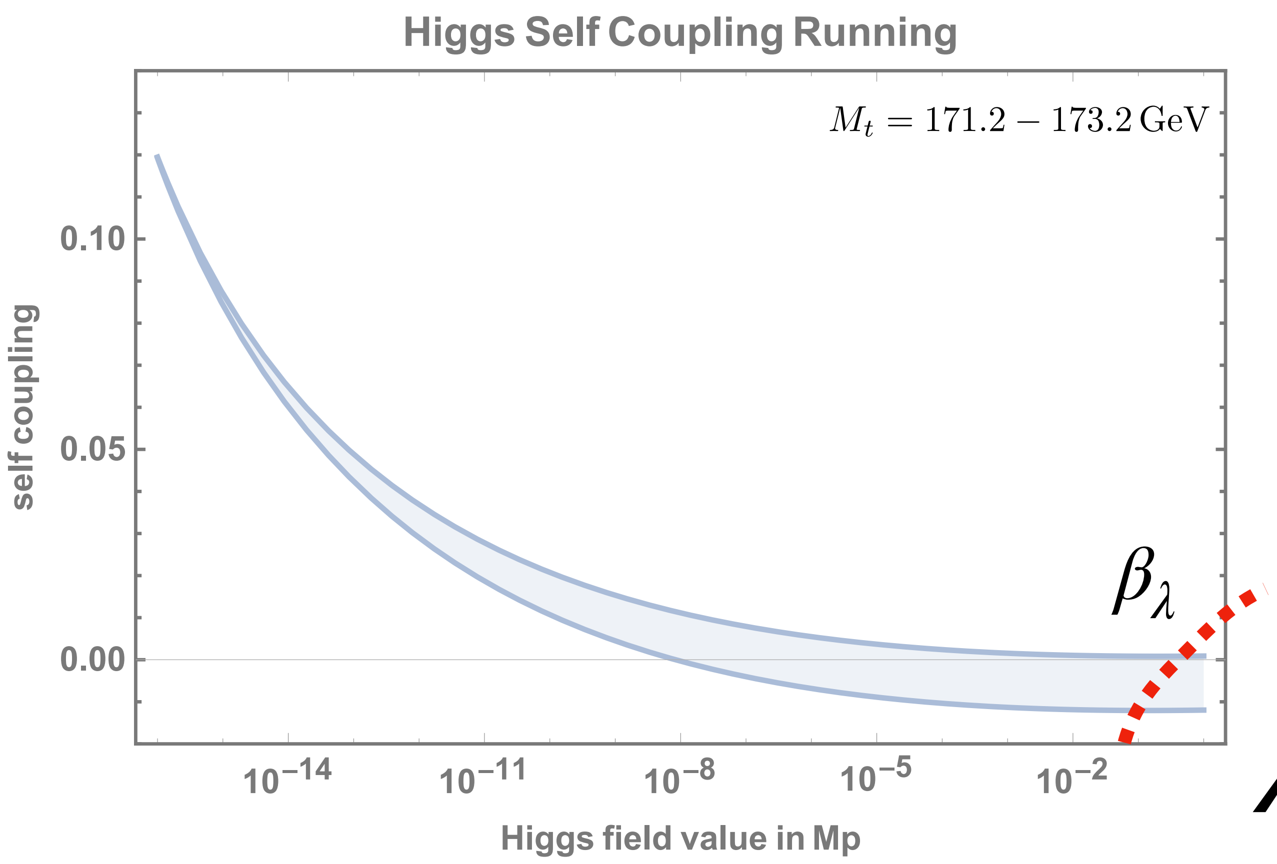
$$\frac{d\lambda}{d\log\mu} = \quad \begin{aligned} \beta_\lambda = {} & \frac{1}{(4\pi)^2}\left[24s^2\lambda^2 - 6y_t^4 + \frac{3}{8}\left(2g^4 + (g^2+g'^2)^2\right) + \left(-9g^2 - 3g'^2 + 12y_t^2\right)\lambda\right] \\ + {} & \frac{1}{(4\pi)^4}\left[\frac{1}{48}\left(915g^6 - 289g^4g'^2 - 559g^2g'^4 - 379g'^6\right) + 30sy_t^6 - y_t^4\left(\frac{8g'^2}{3} + 32g_s^2 + 3s\lambda\right)\right. \\ + {} & \lambda\left(-\frac{73}{8}g^4 + \frac{39}{4}g^2g'^2 + \frac{629}{24}sg'^4 + 108s^2g^2\lambda + 36s^2g'^2\lambda - 312s^4\lambda^2\right) \\ + {} & \left. y_t^2\left(-\frac{9}{4}g^4 + \frac{21}{2}g^2g'^2 - \frac{19}{4}g'^4 + \lambda\left(\frac{45}{2}g^2 + \frac{85}{6}g'^2 + 80g_s^2 - 144s^2\lambda\right)\right)\right]. \qquad (33) \end{aligned}$$

$$< 0$$

==> Higgs self-coupling becomes weaker at higher scales!

RG running of λ

At high scale, the Higgs self-interaction & its variation become feeble



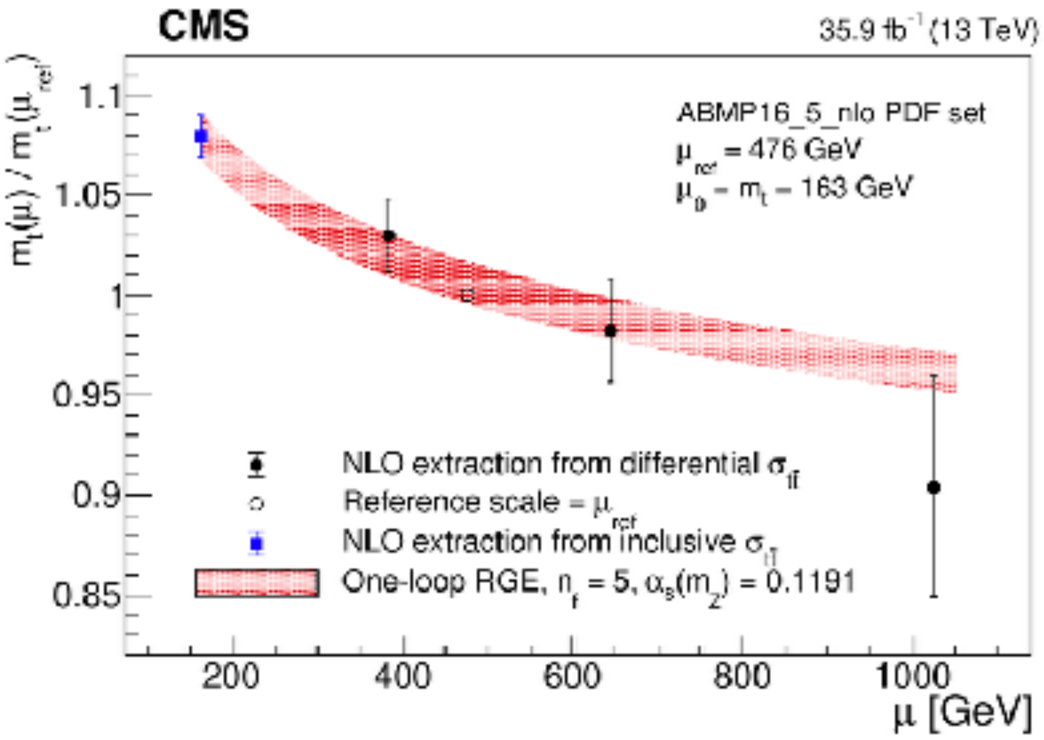
Higgs Criticality!

$$\lambda \approx 0 \approx \lambda'$$

Hamada, Kawai, Oda, <u>SCP</u> (PRL 2014)

Running top mass

(measured for the first time)



~ consistent with the critical Higgs

CMS-TOP-19-007 ; CERN-EP-2019-189

Critical Higgs

$$\lambda \approx \lambda' \approx 0$$ near Planck scale

Meaning: Higgs force is vanishing near M_{Pl}

Higgs Inflation

[Futamase, Louis, Maeda (1987)] [Jai-chan Hwang (1997)]
[Bezrukov, Shaposhnikov *(2007)*] [SCP, Yamaguchi *(2008)*]**
**for general nm-coupling

** In EFT, you are not allowed to get rid of it without a good reason to forbid it

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

@ large field

$$V_J(\phi_J) = \frac{\lambda}{4}\phi_J^4$$

Weyl transformation

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

$$\psi \to \Omega^{\mathscr{D}}\psi \qquad \mathscr{D} = \begin{cases} 3/2, & \text{fermion} \\ 1, & \text{boson} \end{cases}$$

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

The potential in Einstein frame:
(where gravity is normal)

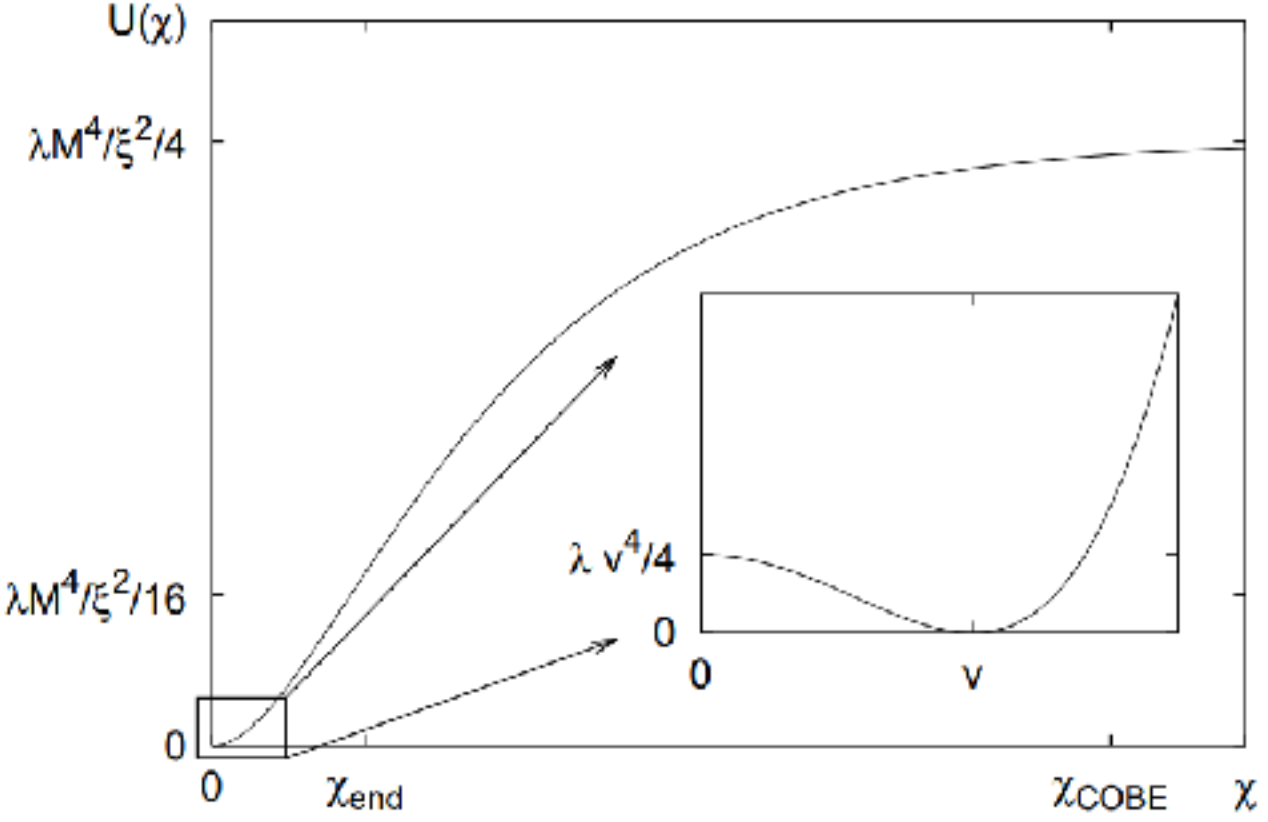
@ large field

$$V = \frac{V_J}{\Omega^4} = \frac{\lambda\phi^4}{\left(1+\xi^2\phi^2\right)^2} \to \frac{\lambda M_P^4}{4\xi^2} = const\,.$$

"Flat potential" ~ slow roll inflation

Higgs Inflation

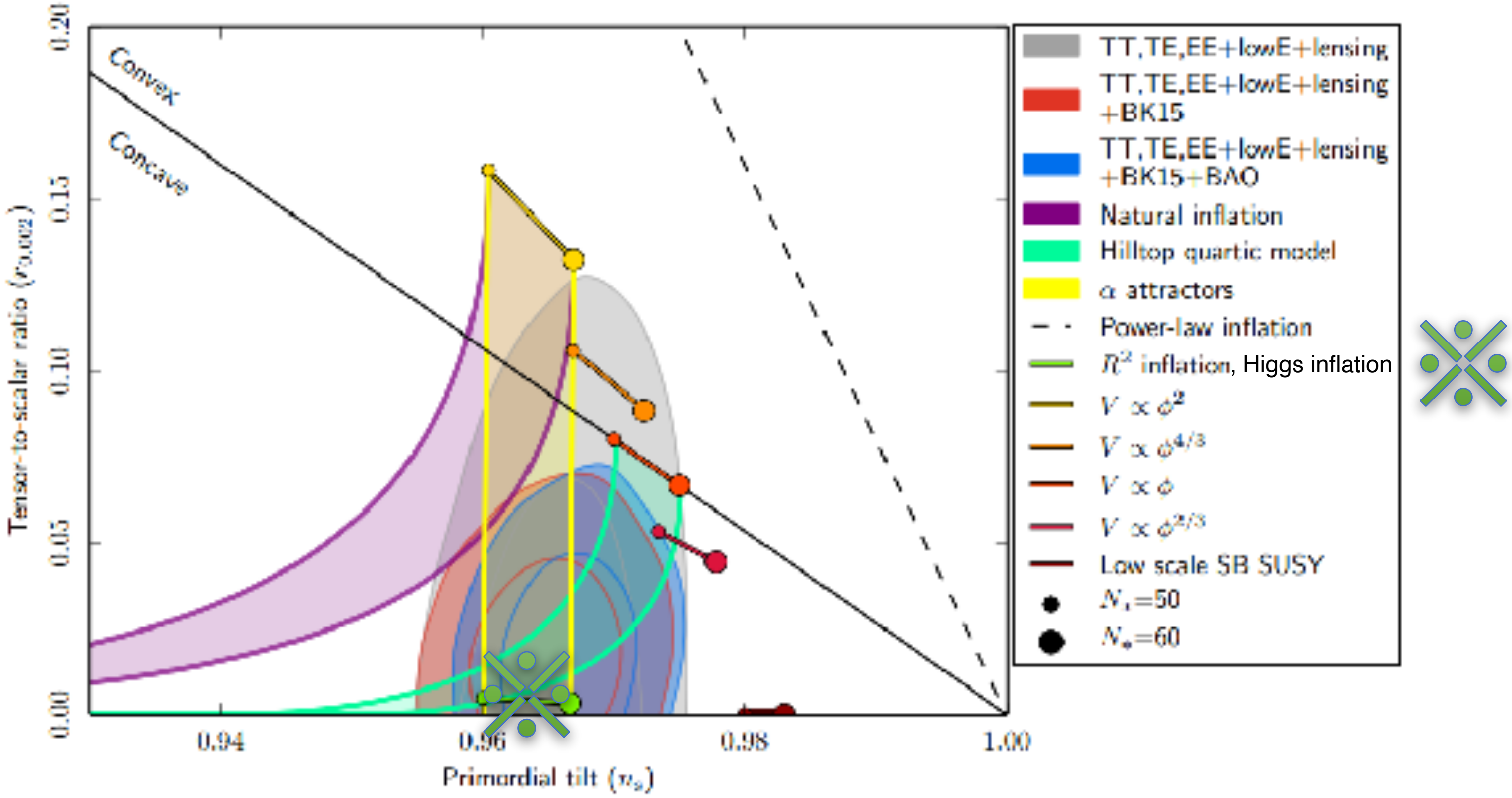
[Futamase, Louis, Maeda (1987)] [Jai-chan Hwang (1997)]
[Bezrukov, Shaposhnikov *(2007)*] [SCP, Yamaguchi *(2008)*]



Higgs Inflation

[Futamase, Louis, Maeda (1987)] [Jai-chan Hwang (1997)]
[Bezrukov, Shaposhnikov *(2007)*] [SCP, Yamaguchi *(2008)*]

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



Higgs inflation $\leftrightarrow$ Starobinsky Inflation

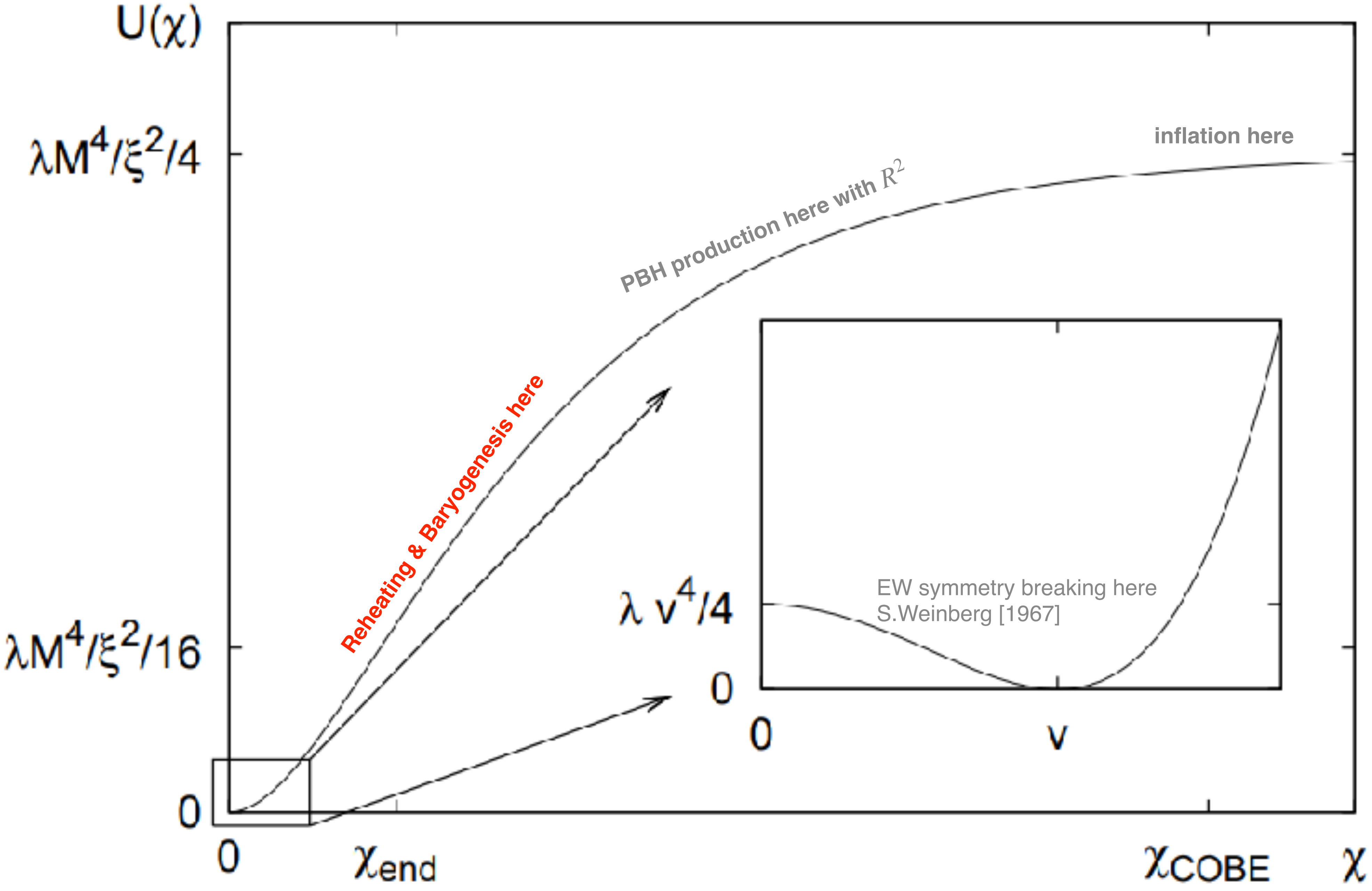
- $S_{\text{Starobinsky}} = \int d^4x\sqrt{-g}\left(\frac{M^2}{2}R + c_S R^2\right)$ explains the inflation if $c_S \sim 10^{10}$ (WMAP) Starobinsky (1980)

- $S_{\text{Higgs}} = \int d^4x\sqrt{-g}\left(\frac{M^2+\xi h^2}{2}R - \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}h^4 + \cdots\right)$ neglecting kinetic term during inflation, then take the field h as auxiliary. Solve EOM by taking δh or $(\xi h R - \lambda h^3)\delta h = 0$ leads to $h^2 = \frac{\xi}{\lambda}R$

- $S_{\text{Higgs}} = \int d^4x\sqrt{-g}\frac{M^2 + \xi \overbrace{h^2}^{\xi R/\lambda}}{2}R - \frac{\lambda}{4}\overbrace{h^4}^{\xi^2R^2/\lambda^2} = \int d^4x\sqrt{-g}\left(\frac{M^2}{2}R + \frac{\xi^2}{4\lambda}R^2 + \cdots\right) = S_{\text{Starobinsky}}$

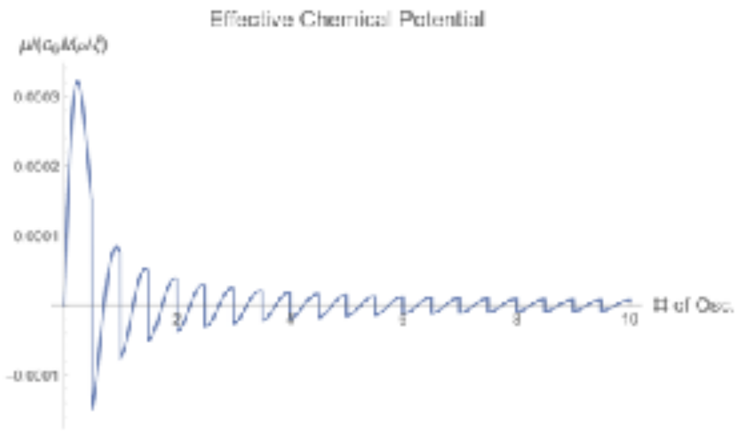
- Matching condition $\therefore c_S = \frac{\xi^2}{4\lambda} \sim 10^{10}$ This is really consistent with CRITICAL HIGGS $\lambda \ll 1, \xi \sim 1$.

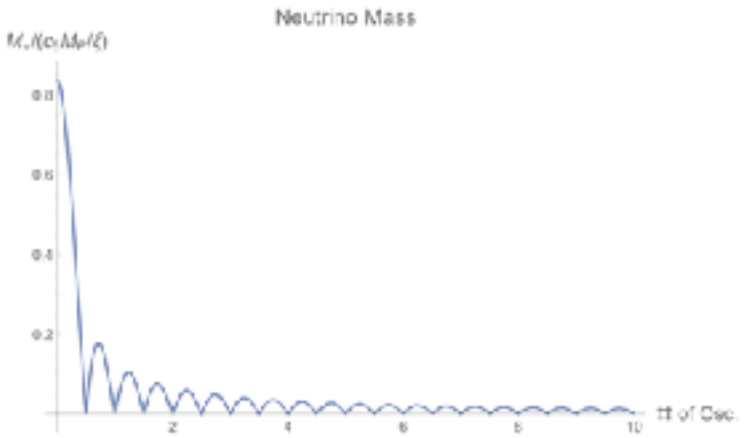
Hamada, Kawaii, Oda, SCP, PRL(2014)



U(χ)
λM⁴/ξ²/4
λM⁴/ξ²/16
0
0
χend
χCOBE
χ
inflation here
PBH production here with R^2
Reheating & Baryogenesis here
λ v⁴/4
0
0
v
EW symmetry breaking here
S.Weinberg [1967]

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 : $m \to \dfrac{m(t)}{\Omega(t)}$
- 'Change of mass' can be understood as change of vacuum
  ==> **Bogoliubov transformation** ==> Particle Production (just like Hawking Radiation!)
- 



$\Rightarrow$ **Particle Production**

Higher Dimension Operators : Dim-5

SM is an EFT

- In general, we do have higher order operators, which are suppressed by cut-off scale (M_P) as long as the symmetry.
- Weinberg Operator : $\mathcal{O}_W = \frac{c_5}{M_P} \bar{L}^c \Phi_J \Phi_J^\dagger L$
  - Source of Lepton Number Violation
  - Generating neutrino mass (time dependent)
  - Right-handed Majorana neutrino can be the UV origin of the operator $M_N \sim 10^{15}\mathrm{GeV}, T_{\mathrm{reh}} \leq 10^{15}\mathrm{GeV}$

Higher Dimension Operators : Dim-6

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

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

  - As Higgs field is the inflaton, the dynamics of the 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

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

occupation number $f_s(t,k)$

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

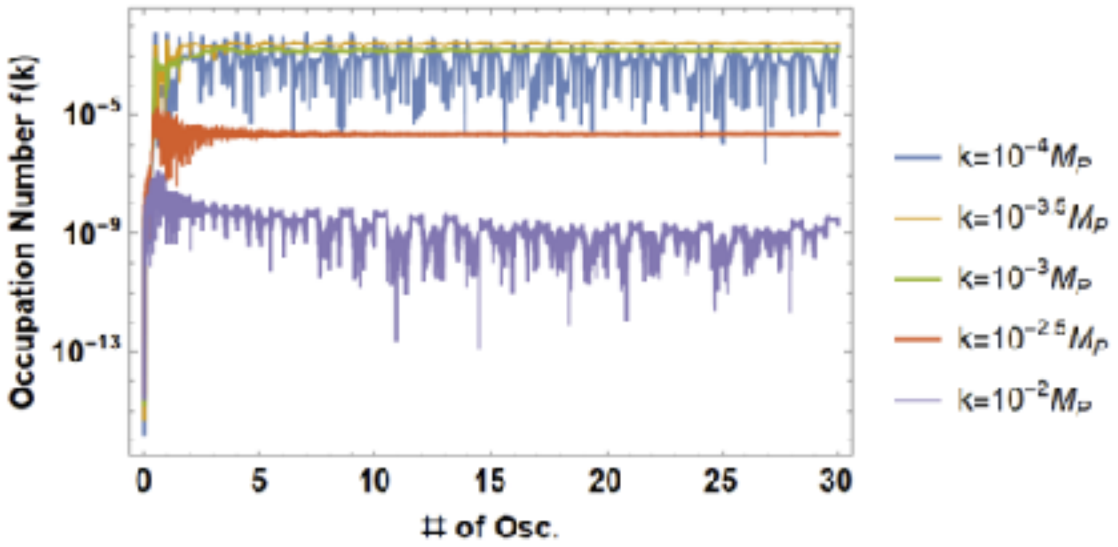
$$n_L|_{\rm reh} \equiv \lim_{t\to t_{\rm reh}} n_\ell(t) - n_{\bar{\ell}}(t)$$

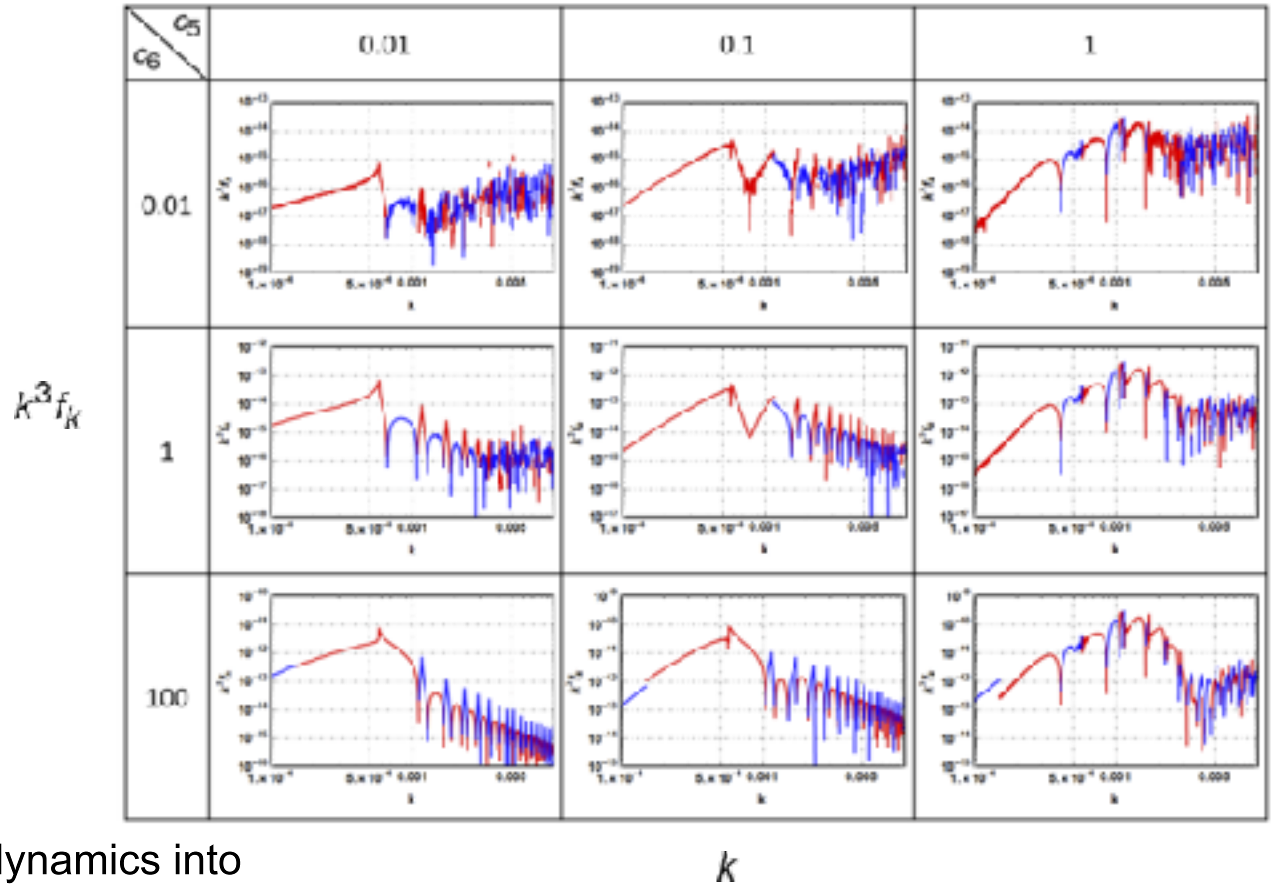
$$\eta_L(t_{\rm reh}) \equiv \left.\frac{n_L}{n_\gamma}\right|_{\rm reh} = \frac{\pi^2}{2\zeta(3)}\left.\frac{\tilde{n}_L}{\tilde{T}^3}\right|_{\rm reh}$$

- transforms to B asymmetry via sphaleron

Lepton Asymmetry

Occupation number for
particle, anti-particle





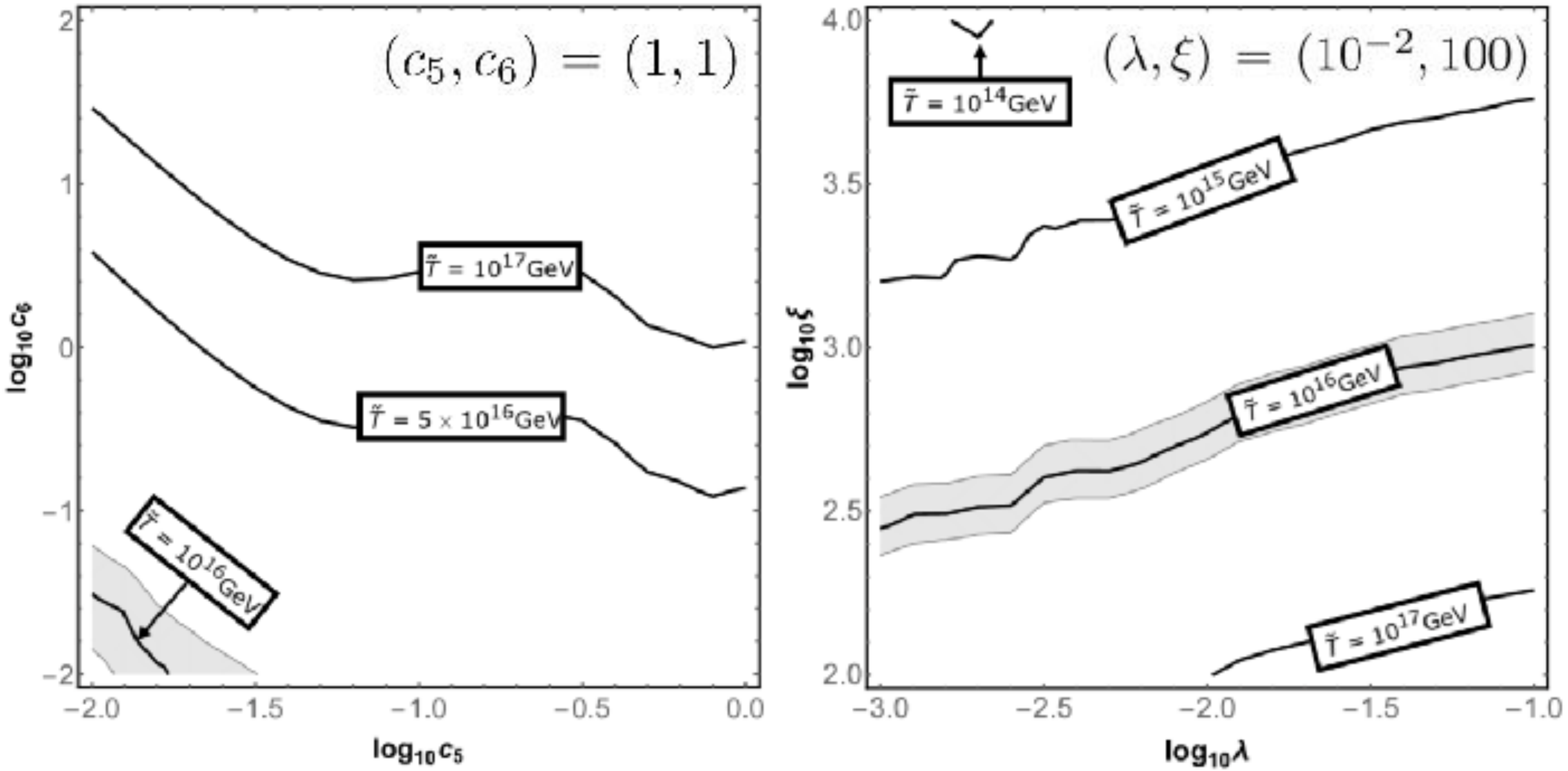
- Perform numerical computation taking actual inflationary dynamics into account
- It turned out that almost all asymmetry is produced at early time (≤ 5 osc.)

→ Insensitive to the details of late time reheating history

[Lee, Oda, SCP. 2010.07563]

Results for observed B-asymmetry

$$\eta_B(c_5, c_6, \widetilde{T}) \simeq \frac{C^{(\mathrm{SM})}_{\mathbf{sphal}} \pi^2 \widetilde{n}_L{}^{(c_5, c_6)}}{2\zeta(3)\widetilde{T}^3} \qquad \tilde{T} = T_{\mathrm{reh}} \frac{a_{\mathrm{reh}}}{a_{\mathrm{end}}}$$



[Lee, Oda, SCP. 2010.07563]

Summary & Conclusion

- Maybe Higgs physics is much more profound than we've thought. (EWSB + inflation + reheating + PBH as DM + Matter-anti-Matter asymmetry)
- Coherently oscillating Higgs field as inflaton provides natural possibility of spontaneous leptogenesis during the reheating:
  - Weinberg operator : Lepton number violation, neutrino masses (time dependent)
  - Higgs-Lepton current interaction : Chemical potential for asymmetrical production of Lepton & anti-Lepton

  with large reheating temperature with $10^{15}\ \mathrm{GeV} = T_{\mathrm{reh}}\frac{a_{\mathrm{reh}}}{a_{\mathrm{end}}} < 10^{18}\ \mathrm{GeV}$.
- Future collider experiments ($m_t, \alpha_s, \lambda_{hhhh}, \lambda_{hhh}, \cdots$) and astrophysical observations ($n_s, r, PBH, \cdots$) will provide direct/indirect probes to our scenario.