Baryogenesis in false vacuum

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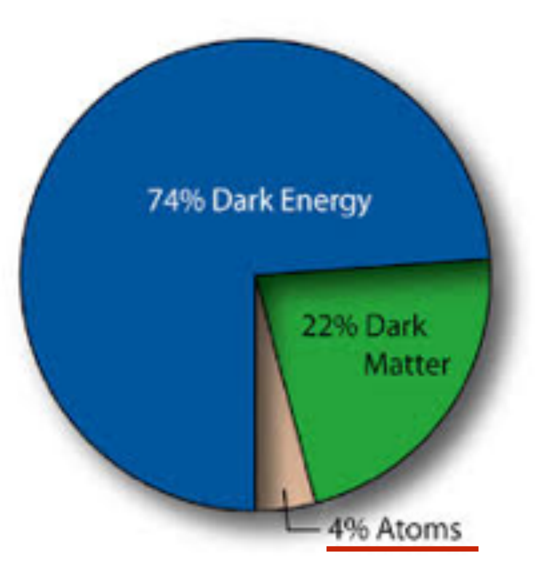
Discovery of Higgs boson

- M_H=125GeV.
- consistent with SM prediction.
- SM is completed.

Baryogenesis

- There remains mystery in particle physics.
- We do not understand
  - dark energy
  - dark matter
  - why energy density of atom is so large.(baryon asymmetry)



$$\frac{n_B}{s} \simeq (8.68 \pm 0.05) \times 10^{-11}$$

Sakharov's three conditions

1. Violation of baryon number
2. Violation of C and CP
    - Initial state : C and CP symmetric
      Final state : C and CP asymmetric
3. Out of thermal equilibrium
    - otherwise inverse process exists.

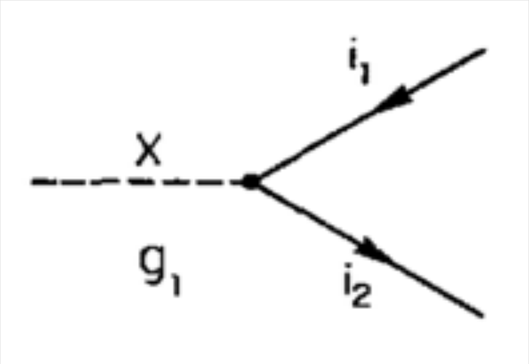
Conditions in SM

1. Violation of baryon number
   - ★ sphaleron process breaks B+L number.
2. Violation of C and CP
   - ★ CKM phase, strong θ term
3. Out of thermal equilibrium
   - ★ impossible within SM

Decay of heavy particle

[Yoshimura 1978]

- Conventional scenario: Decay of heavy particle, X



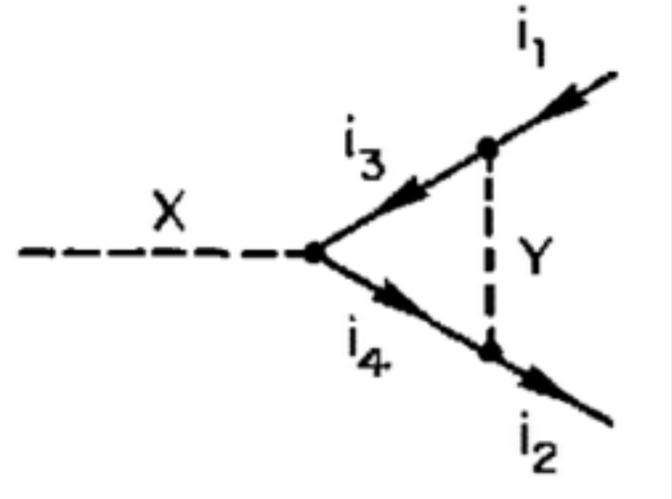
- decay rate ∝ $|M|^2$

- no asymmetry@tree level $\Gamma(X \to \bar{i}_1 i_2) - \Gamma(\bar{X} \to i_1 \bar{i}_2) = 0$

$$\mathcal{L} = g_1 X i_2^\dagger i_1 + g_2 X i_4^\dagger i_3 + g_3 Y i_1^\dagger i_3 + g_4 Y i_2^\dagger i_4 + h.c.$$

Decay of heavy particle2

- One-loop diagram



- If both of coupling&loop integral I has imaginary part, the difference between baryon and anti baryon appears.

$$\Gamma(X \to \bar{i}_1 i_2) - \Gamma(\bar{X} \to i_1 \bar{i}_2) \propto \mathrm{Im}(I)\mathrm{Im}(g_1^* g_2 g_3^* g_4)$$

observation

- Now we have the standard model.
- (Maybe) Neutrino Majorana mass

$$\frac{\lambda_{ij}}{\Lambda_1} H H \bar{L}_j^c L_i$$

ν mass～0.1eV after EWSB

observation2

- Higgs mass may indicate that SM is valid up to very high scale.
- In the early universe, the Higgs field may develop the large field value.
- Then, the lepton number is strongly violated in high scale minimum.
- We utilize this for baryogenesis.

$$\frac{\lambda_{ij}}{\Lambda_1} H H \bar{L}_j^c L_i$$

- Decay of left handed neutrino may generate asymmetry.

Plan

1. What happens if
   <H> >> (EW scale) @ early universe
2. Thermal history

Mass spectrum

- Masses as functions of Higgs VEV, <H>.

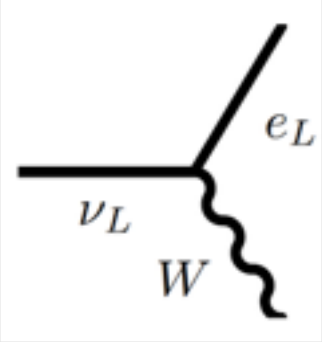
$$M_\nu = \frac{\langle H \rangle^2}{\Lambda_1} \qquad\qquad M_W = \frac{1}{2} g_2 \langle H \rangle$$

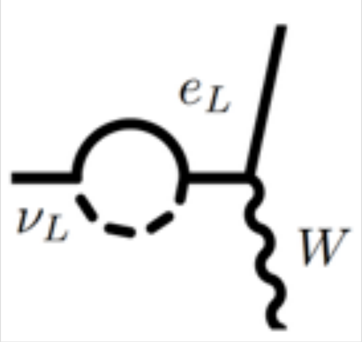
$$\Lambda_1 = 6 \times 10^{14} \mathrm{GeV} \left(\frac{0.1 \mathrm{eV}}{M_\nu} \right)$$

- For <H> >> (EW scale),
  these particles are supermassive.

Decay of ν_L

- The decay of the left handed neutrino



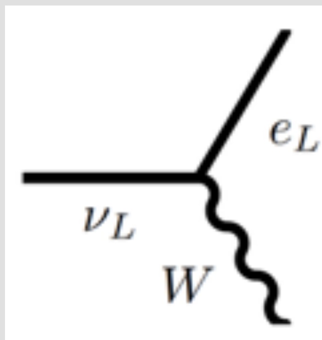


neutrino mass should be larger than W mass.
roughly,

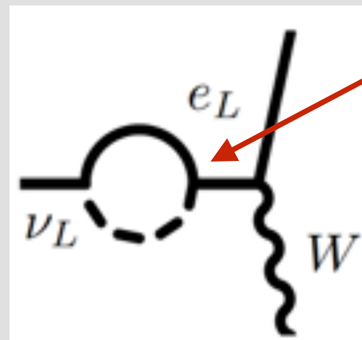
$$\langle H \rangle > \frac{g_2}{2}\Lambda_1 \simeq 1.5 \times 10^{14}\mathrm{GeV}$$

Interesting point

- The decay of the left handed neutrino



charged lepton Yukawa



CP phase is Dirac phase in PMNS matrix, which will be measured by future neutrino oscillation experiment.

Boltzmann equation

$N_i = n_i / n_\gamma$, $X = \nu_L$, $z = M_\nu / T$

$$\frac{d}{dz}N_X = -\left(\frac{\Gamma_X(z)}{H(z)z}\right)(N_X - N_X^{\rm EQ}) - \left(\frac{\langle\sigma_{\rm ann}v\rangle\, n_\gamma}{H(z)z}\right)\left(N_X^2 - \left(N_X^{\rm EQ}\right)^2\right)$$

decay&inverse decay

pair annihilation

ν decay

washout by inverse decay

$$\frac{d}{dz}N_{B-L} = -\left(\frac{2\epsilon\Gamma_X(z){\rm Br}}{H(z)z}\right)(N_X - N_X^{\rm EQ}) - 4N_{B-L}\left(\frac{\Gamma_X(z){\rm Br}}{H(z)z}\right)N_X^{\rm EQ} - \left(\frac{\langle\sigma_L v\rangle\, n_\gamma}{H(z)z}\right)4N_{B-L}N_l,$$

washout by 2→2 scattering

functions

- decay rate

$$\Gamma_X(z) = \frac{1}{\gamma} \frac{M_\nu}{8\pi} \left(\frac{\langle H \rangle}{\sqrt{2}\Lambda} + g_2 \right)^2$$

- interference between tree&one-loop

$$\epsilon \simeq \sum_{j=2,3} \frac{\mathrm{Im}(YY^\dagger)_{1i}}{8\pi} \frac{M_{\nu,i}}{M_{\nu,1}} \frac{1}{1 - M_{\nu,i}^2/M_{\nu,1}^2}$$

- pair annihilation

$$\sigma_{\rm ann} v = \alpha_2^2 \frac{1}{M_\nu^2} \qquad \sigma_L v = \alpha_2^2 \frac{1}{M_\nu^2}$$

sphaleron process

- sphaleron converts the lepton number into the baryon number.

$$n_B = \frac{8N_F + 4N_S}{22N_F + 13N_S} n_{B-L}$$

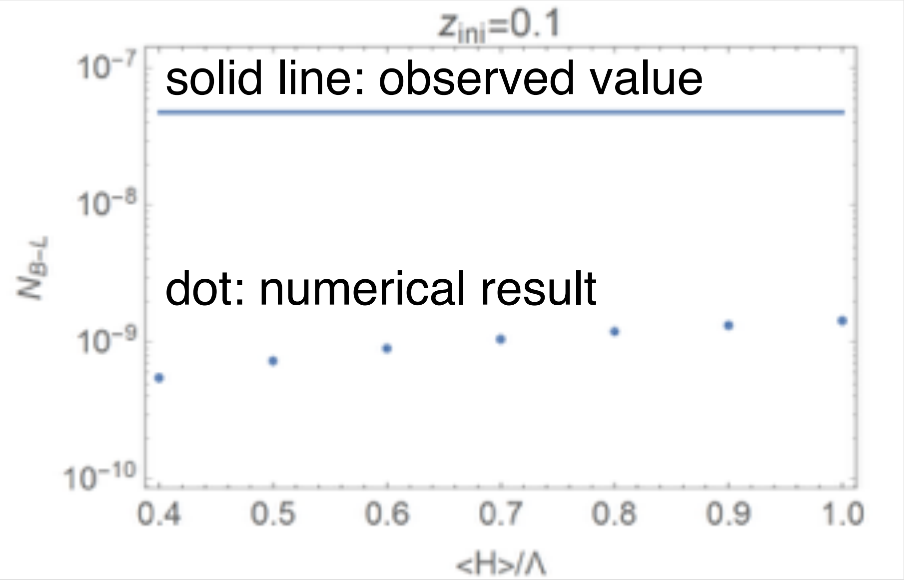
N_F: number of generation

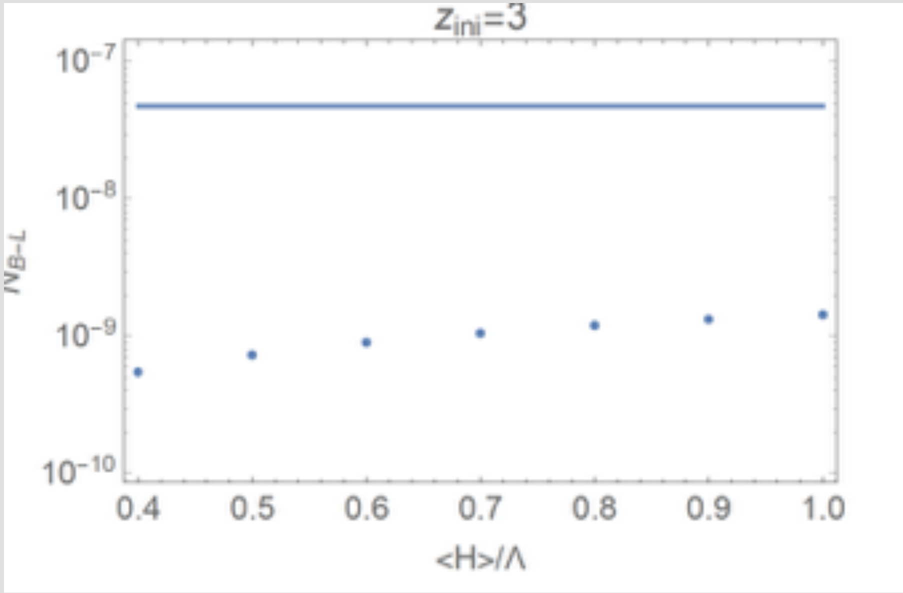
N_S: number of doublet scalar

- 28/79 in the SM case.

Result

- w/ zero initial condition ($N_\nu = N_{B-L} = 0$ @ z_{ini})
  - $M_{\nu,lightest}$=0.1eV, maximum CP phase.





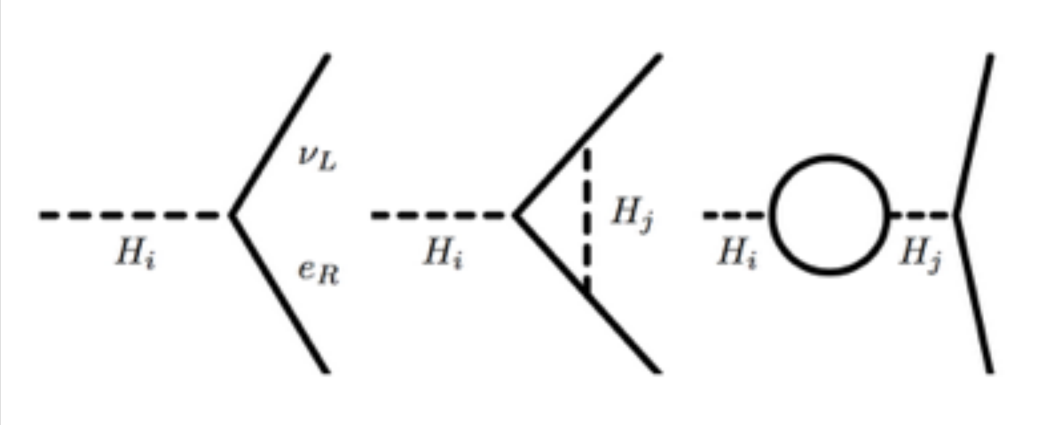
- below the observation value…

Two Higgs doublets

- If we add the second Higgs boson,

$$\Delta\mathcal{L} = y_{2,ij}\bar{E}_i H_2 L_j + \cdots$$

the asymmetry increases by the decay of charged Higgs boson.



functions

- decay rate

$$\Gamma_X(z) = \frac{1}{\gamma}\frac{M_{H_2}}{8\pi}\left(y_2^2 + \frac{h^2}{2\Lambda^2}\right)$$

- interference between tree&one-loop

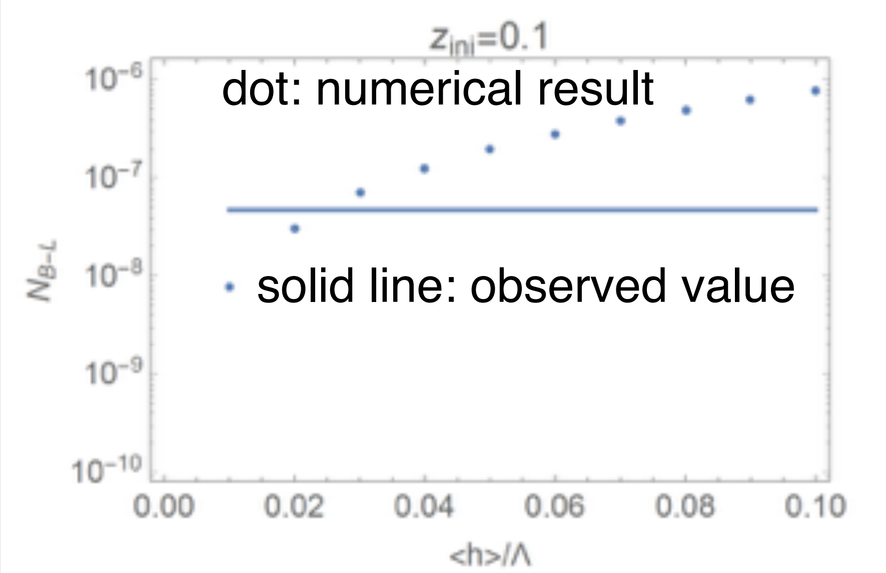
$$\epsilon \simeq \sum_{i,j=1\cdots 3} \frac{\mathrm{Im}(y_2 y_2^\dagger)_{ij}^2}{8\pi(y_2 y_2^\dagger)_{ij}}\frac{M_\nu}{M_{H_2}}$$

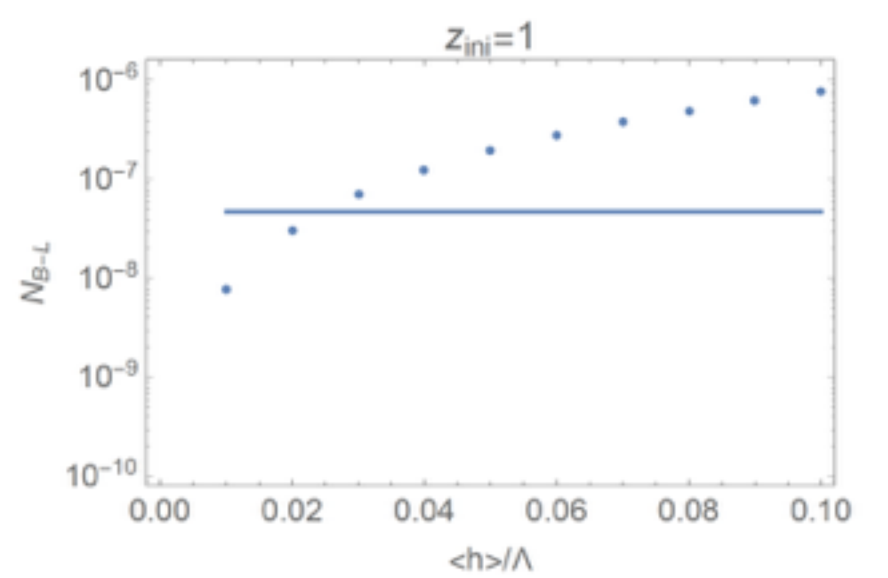
- pair annihilation

$$\sigma_{\mathrm{ann}} v \simeq \alpha_2^2 \frac{1}{M_{H_2}^2} \qquad \sigma_L v \simeq \left(\frac{y_2^2}{4\pi}\right)^2 \frac{1}{M_{H_2}^2}$$

Result2

- $|y_{2ij}|=1$, maximum CP.





Plan

1. What happens if
   <H> >> (EW scale) @ early universe

2. Thermal history

How to realize <H> >> (EW scale) in early universe,
<H> = (EW scale) in current universe.

scalar potential(T=0)

- We add singlet scalar S.
- Tree-level potential

$$V_{\rm tree}(h,S) = -\kappa \frac{m_S^2}{4\lambda_S} h^2 + \frac{1}{4}\lambda h^4 + \kappa h^2 S^2 - \frac{1}{2} m_S^2 S^2 + \lambda_S S^4$$

- h: Higgs boson, S: SM singlet scalar
- position of minimum

$$\langle h \rangle = 0,\ \langle S \rangle = \frac{1}{2}\sqrt{\frac{m_S^2}{\lambda_S}}$$

Thermal correction

$$V = V_{\text{tree}}(h, S) + V_{FT}(h, S, T) + V_{\text{RING}}(h, S, T)$$

finite temperature part

$$V_{\text{FT}}(h, T) = \frac{T^4}{2\pi^2}\Big[J_B(\tilde{m}_h^2(T)/T^2) + 6J_B(\tilde{m}_W^2/T^2) + 3J_B(\tilde{m}_Z^2/T^2) - 12J_F(\tilde{m}_t^2/T^2)\Big]$$

$$J_B(r^2) = \int_0^\infty dx\, x^2 \ln\left(1 - e^{-\sqrt{x^2+r^2}}\right), \quad J_F(r^2) = \int_0^\infty dx\, x^2 \ln\left(1 + e^{-\sqrt{x^2+r^2}}\right)$$

$$V_{\text{RING}}(h, T) = -\frac{T}{12\pi}\Big(2a_g^{3/2} + \frac{1}{2\sqrt{2}}(a_g + c_g - [(a_g - c_g)^2 + 4b_g^2]^{1/2})^{3/2}$$
$$+\frac{1}{2\sqrt{2}}(a_g + c_g + [(a_g - c_g)^2 + 4b_g^2]^{1/2})^{3/2} - \frac{1}{4}[g^2h^2]^{3/2} - \frac{1}{8}[(g^2 + g'^2)h^2]^{3/2}\Big)$$

$$a_g = \frac{1}{4}g^2h^2 + \frac{11}{6}g^2T^2, \qquad b_g = -\frac{1}{4}gg'h^2, \qquad c_g = \frac{1}{4}g'^2h^2 + \frac{11}{6}g'^2T^2$$

Higgs potential for various T

- At high temperature, symmetry is restored.

$$V_{\rm tree}(h,S) = -\kappa\frac{m_S^2}{4\lambda_S}h^2 + \frac{1}{4}\lambda h^4 + \kappa h^2 S^2 - \frac{1}{2}m_S^2 S^2 + \lambda_S S^4$$

$$\langle h\rangle = 0, \langle S\rangle = 0$$

- Utilizing high temperature expansion, critical temperatures of h&S phase transition are

$$T_S = \frac{2\sqrt{3}\sqrt{2v_S^2\lambda}}{\sqrt{\kappa+6\lambda_S}}, T_h = \frac{4\sqrt{6}\sqrt{v_S^2\kappa}}{\sqrt{9g_2^2+3g_Y^2+12y_t^2+8\kappa+12\lambda}}$$

Thermal history

$$V_{\rm tree}(h,S) = -\kappa\frac{m_S^2}{4\lambda_S}h^2 + \frac{1}{4}\lambda h^4 + \kappa h^2 S^2 - \frac{1}{2}m_S^2 S^2 + \lambda_S S^4$$

T

$$\langle h\rangle = 0, \langle S\rangle = 0$$

T_h

$$\langle h\rangle = \sqrt{\frac{2\kappa}{\lambda}}v_S,\ \langle S\rangle = 0$$

T_S

$$\langle h\rangle = 0,\ \langle S\rangle = \frac{1}{2}\sqrt{\frac{m_S^2}{\lambda_S}}$$

Asymmetry can be produced

- Example of successful parameter set:

$$\kappa = 0.7, \lambda_S = 1.5, \lambda = 0.4, \langle h \rangle = 2 \times 10^{13}\text{GeV}$$

$$\downarrow$$

$$T_S \simeq 1.9 v_S \qquad T_S \simeq 2.0 v_S$$

$$N_{B-L} \simeq 2.6 \times 10^{-7} \sin \delta_{CP} \qquad N_{B-L,\text{obs}} = 4.8 \times 10^{-8}$$

- Observed asymmetry is successfully generated.

Summary

- The discovery of the Higgs boson may indicate the flat potential at high scale.
- high scale vacuum appears in the early universe.
- useful for baryogenesis.

Backup

$$\Gamma(X \to \bar{i}_1 i_2) \propto |g_1|^2 + \mathrm{Re}(g_1 g_2^* g_3 g_4^* I)$$

$$\Gamma(\bar{X} \to i_1 \bar{i}_2) \propto |g_1|^2 + \mathrm{Re}(g_1^* g_2 g_3^* g_4 I)$$

$$\Gamma(X \to \bar{i}_1 i_2) - \Gamma(\bar{X} \to i_1 \bar{i}_2) \propto \mathrm{Im}(I)\mathrm{Im}(g_1^* g_2 g_3^* g_4)$$

$$\langle \sigma_{\mathrm{ann}} v \rangle = \begin{cases} \alpha_2^2 \dfrac{1}{T^2} & (T > M_\nu) \\ \alpha_2^2 \dfrac{1}{M_\nu^2} & (T < M_\nu) \end{cases}$$

$$\langle \sigma_L v \rangle = \alpha_2^2 \frac{1}{M_X^2}$$

During inflation

- We can make Higgs take large VEV during inflation by adding

$$\Delta\mathcal{L} = \xi R|\Phi|^2 = -3(1-3w)\xi H|\Phi|^2$$

- $H_{inf} \sim 10^{13}$GeV is enough to destabilize the origin and to make vacuum around $10^{14\text{-}15}$GeV