POST-INFLATIONARY HIGGS RELAXATION AND THE ORIGIN OF MATTER-ANTIMATTER ASYMMETRY

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DARK ENERGY AND MATTER-ANTIMATTER ASYMMETRY

OUTLINE

- **The Higgs Potential**
- **Quantum Fluctuation During Inflation**
- **Higgs Relaxation After Inflation**
- **Leptogenesis via Higgs Field Relaxation**
- **Summary**

Based on:
A. Kusenko, L. Pearce, LY, Phys.Rev.Lett. 114 (2015) 6, 061302

L. Pearce, LY, A. Kusenko, M. Peloso, Phys.Rev. D92 (2015) 2, 023509

LY, L. Pearce, A. Kusenko, Phys.Rev. D92 (2015) 043506

THE HIGGS POTENTIAL

THE HIGGS BOSON

- **In 2012, LHC has found the Higgs boson.**

  $$V(\Phi) = -m^2\Phi^+\Phi + \lambda(\Phi^+\Phi),$$

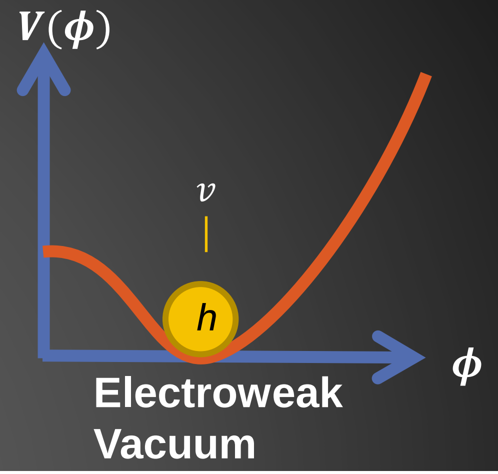
  where $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$.

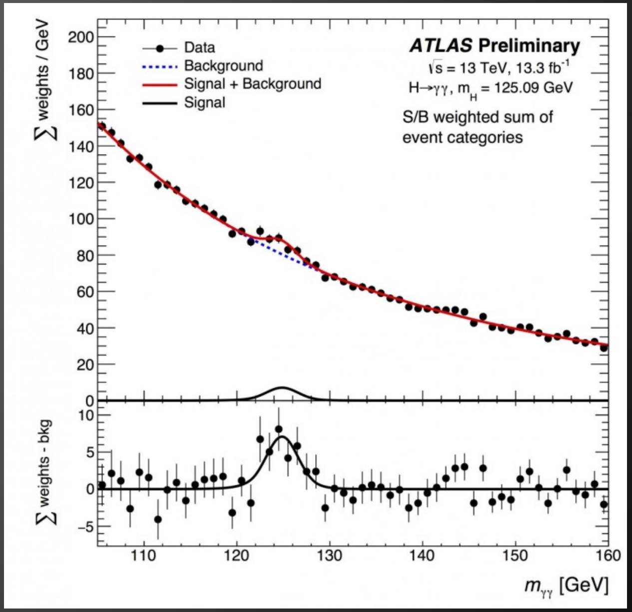
- **Higgs boson mass:**
  $M_h = 125.09 \pm 0.21 \pm 0.11$ **GeV.**

- **A mass smaller than expected!**

- **A small quartic coupling**

  $$\lambda(\overline{\mu} = M_t) \approx M_h^2/2v^2 \approx 0.129$$





C. Patrignani et al.(Particle Data Group),
Chin. Phys. C, 40, 100001 (2016).

RUNNING OF λ

J. Elias-Miro et al., Phys. Lett. B709, 222 (2012)
G. Degrassi et al., JHEP 1208, 098 (2012)
D. Buttazzo et al., arXiv:1307.3536 [hep-ph]

- **QFT: Coupling constants changes with energy scale μ**
- $\beta_\lambda = -\frac{36}{(4\pi)^2} y_t^4 + \cdots$
- **Due to large top mass**
  $$m_t = \frac{1}{\sqrt{2}} y_t v$$
- **If no new physics, $\lambda(h)$ becomes very small and turns negative at $\mu \gtrsim 10^{10} - 10^{12}$ GeV.**

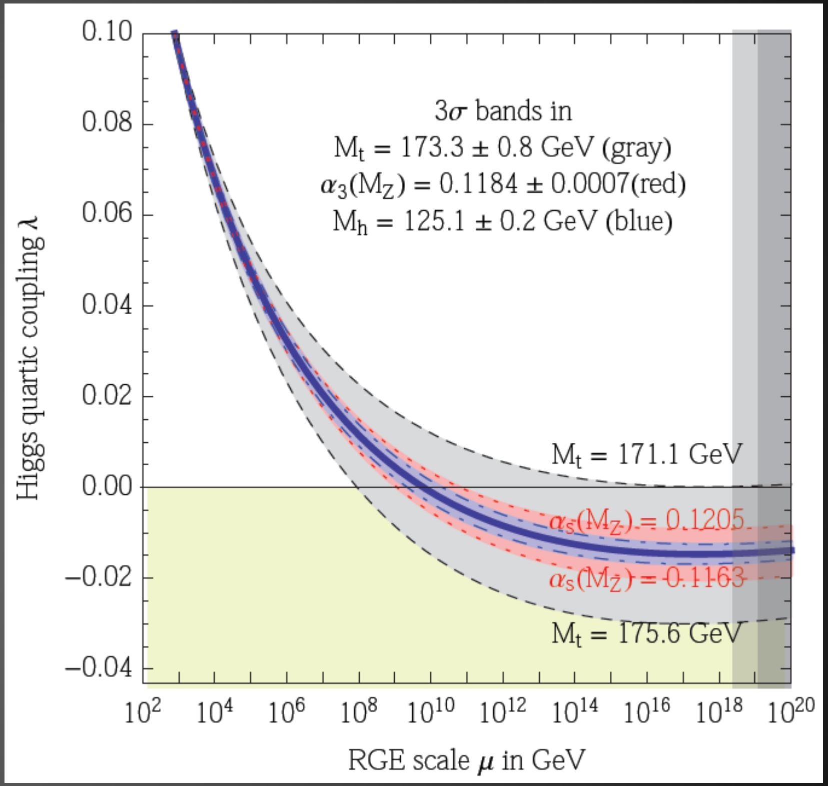
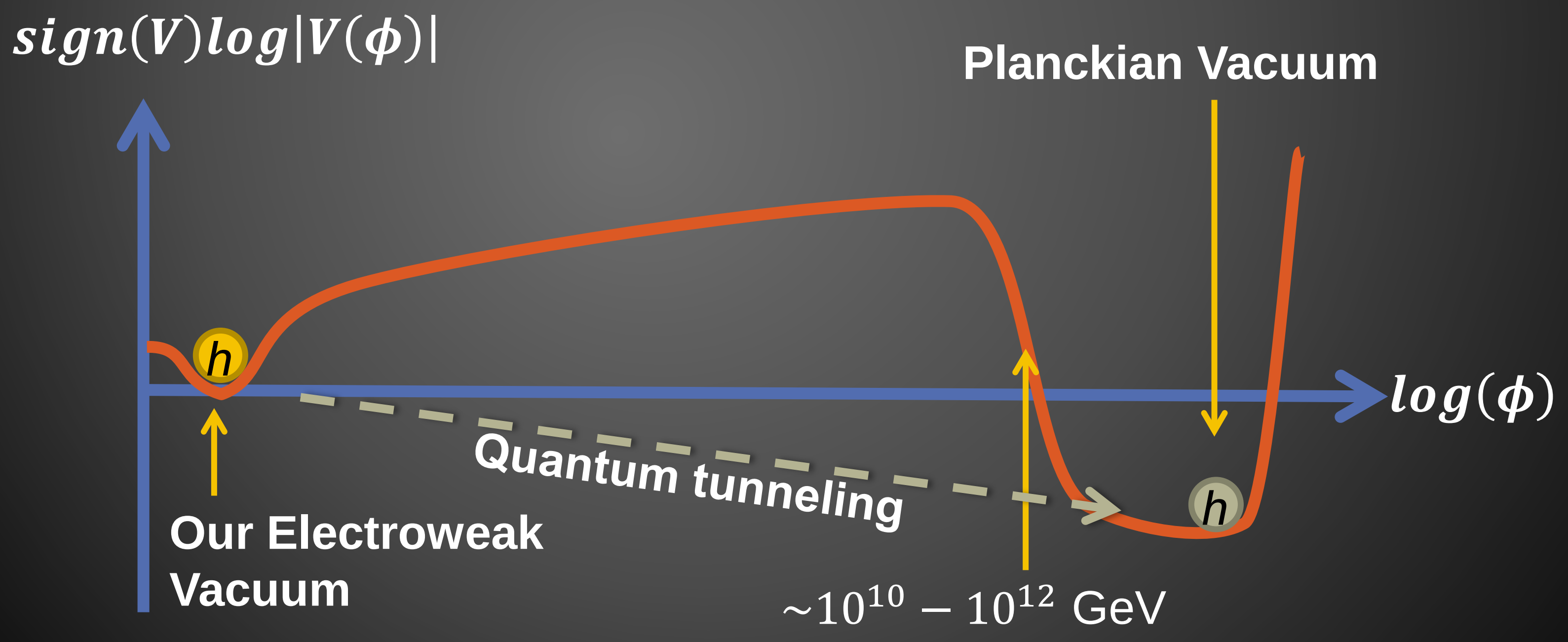


Figure from D. Buttazzo et al., arXiv:1307.3536 [hep-ph]

THE HIGGS EFFECTIVE POTENTIAL

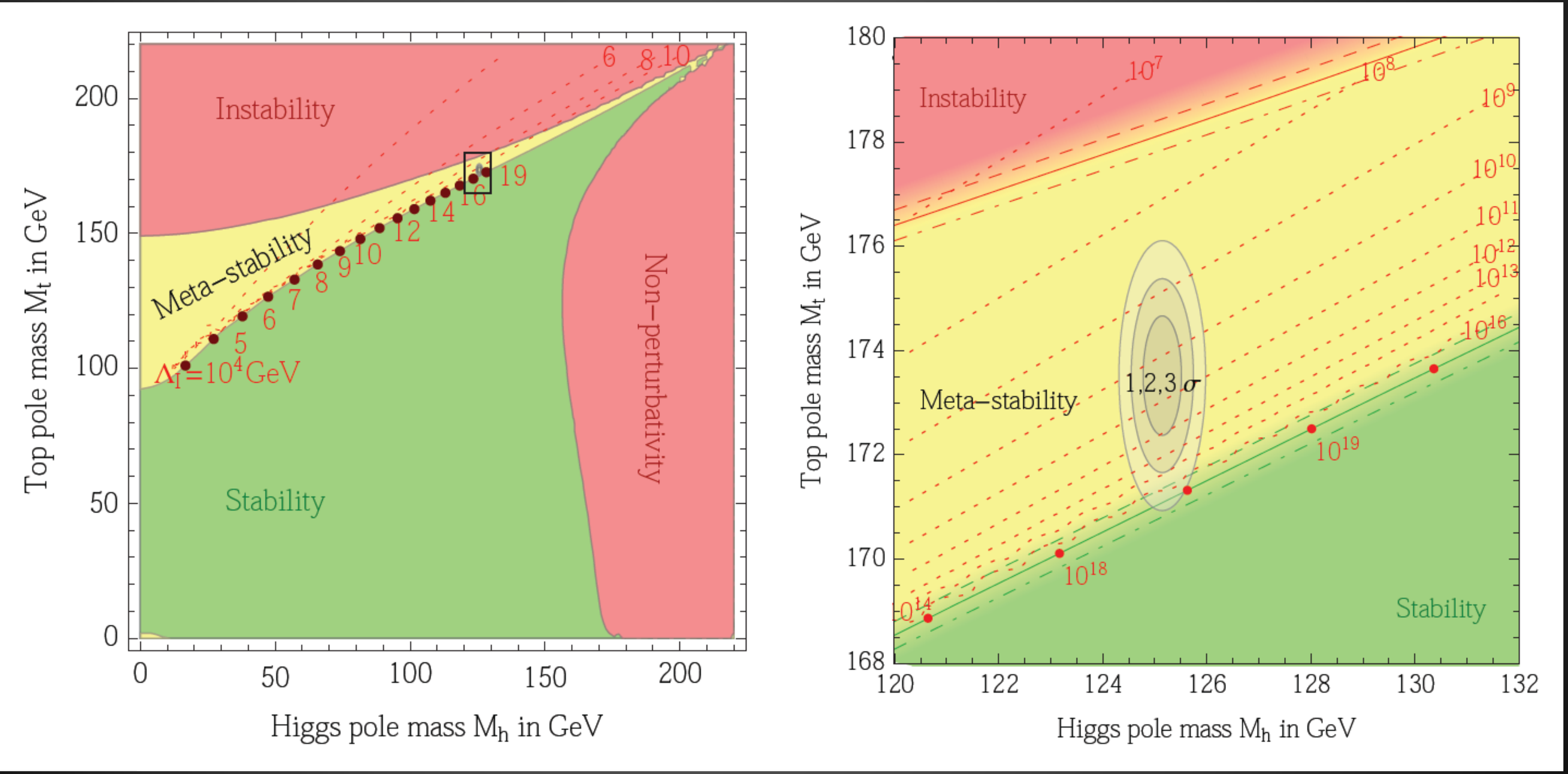
- **Another minimum in the potential: Planckain vacuum!!**
  - Much lower than the electroweak vacuum.
- **Our universe can tunnel into the Planckain vacuum and end in a big crunch!**



META-STABILITY OF OUR VACUUM

J. Elias-Miro et al., Phys. Lett. B709, 222 (2012)
G. Degrassi et al., JHEP 1208, 098 (2012)
D. Buttazzo et al., arXiv:1307.3536 [hep-ph]

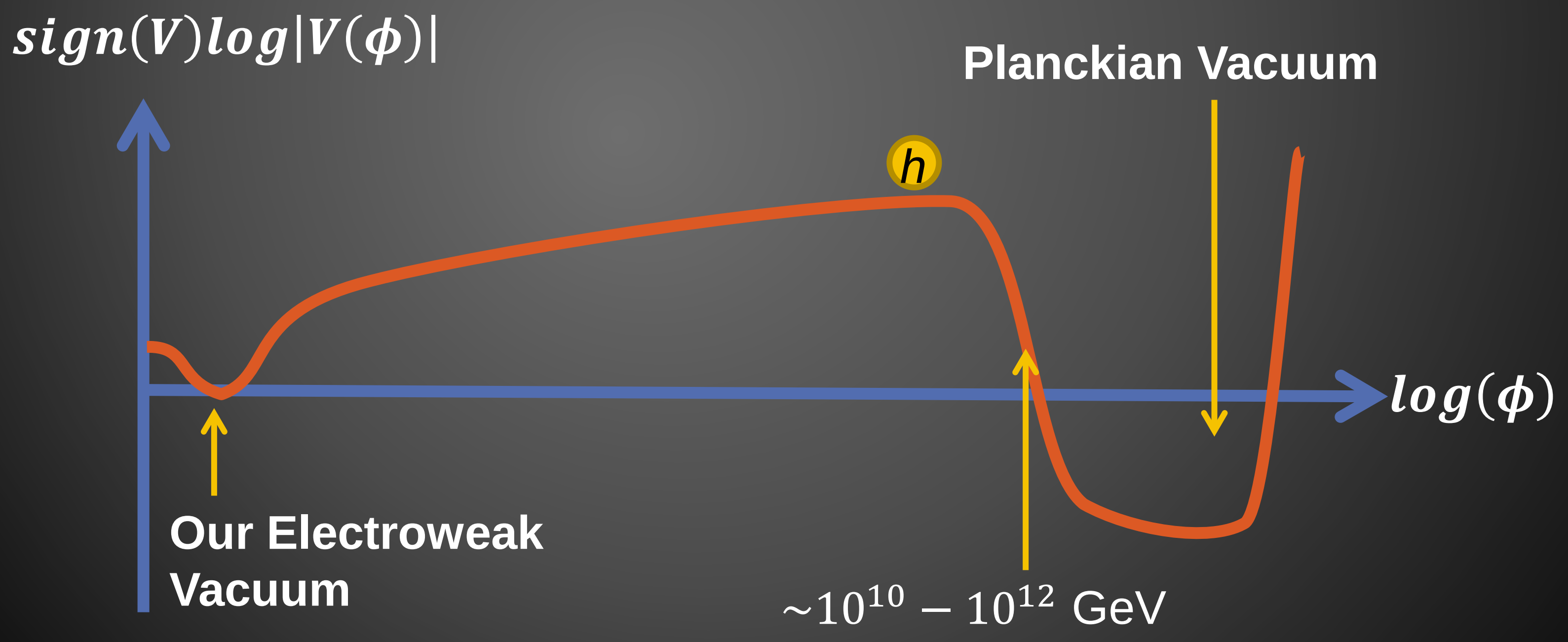
Our universe seems to be right on the meta-stable region.



THE HIGGS EFFECTIVE POTENTIAL

What does it imply?

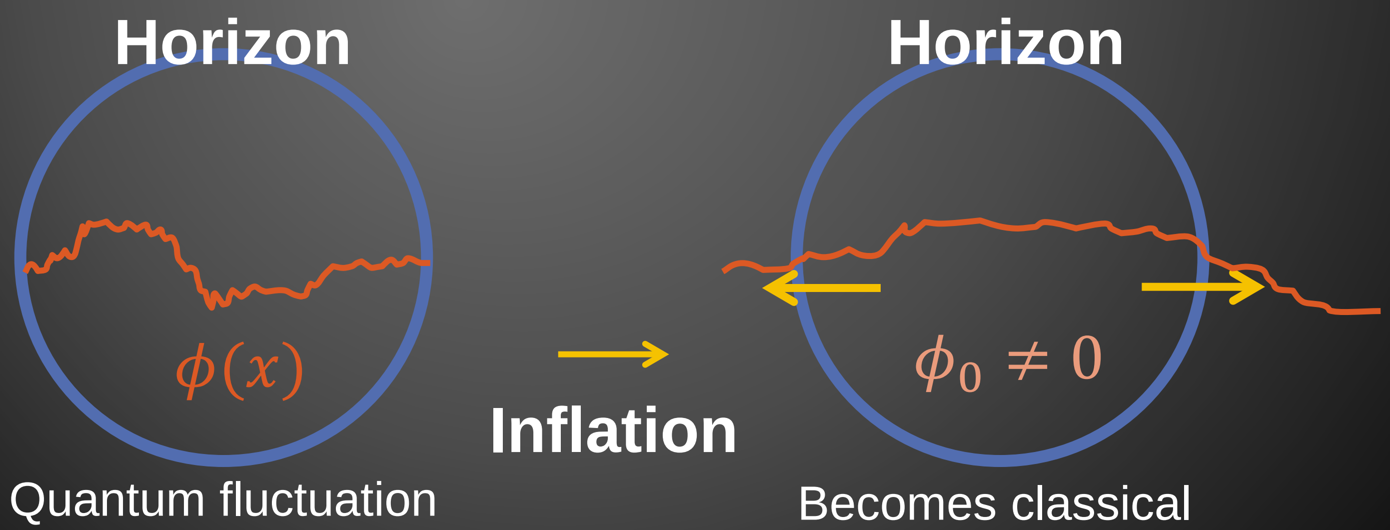
- **A shallow Higgs potential at large scale**
- **A large Higgs VEV during inflation**



QUANTUM FLUCTUATION DURING INFLATION

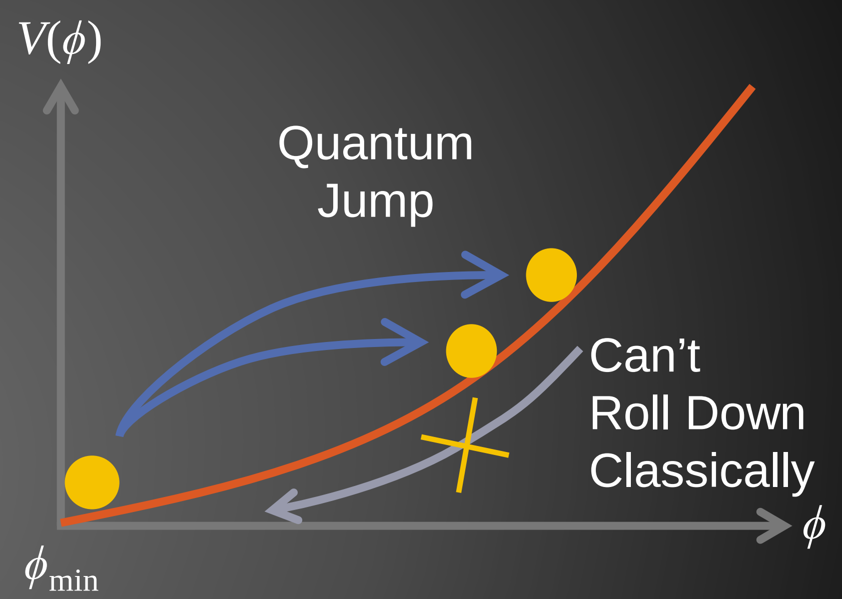
QUANTUM FLUCTUATION DURING INFLATION

- **During inflation, quantum fluctuations get amplified.**
- **They becomes classical when the wavelength exits the horizon.**
- **$\phi(t)$ jumps randomly like Brownian motion.**



QUANTUM FLUCTUATION DURING INFLATION

- **Quantum fluctuation brings the field to non-zero value.**
- **Classical rolling down follows**
  $$\ddot{\phi} + 3H_I\dot{\phi} = -V'(\phi),$$
  which requires
  $$t_{rlx} \sim \left[\frac{d^2V(\phi)}{d\phi^2}\right]^{-1/2} = \frac{1}{m_\phi}$$
- **If $m_\phi \ll H_I$, insufficient time to relax (slow-rolling).**
- **A non-zero VEV of the scalar field is building up.**



Bunch, Davies (1978);
Linde (1982);
Hawking, Moss (1982);
Starobinsky (1982);
Vilenkin, Ford (1982);
Starobinsky, Yokoyama (1994).

LARGE INITIAL VEV OF SCALAR FIELDS

A. A. Starobinsky (1982)
A. Vilenkin (1982)

- **Fokker-Planck equation:**

$$\frac{\partial P_c(\phi,t)}{\partial t} = -\frac{\partial j_c}{\partial \phi} \quad \textbf{where } -j_c = \frac{\partial}{\partial \phi}\left(\frac{H^3 P_c}{8\pi^2}\right) + \frac{P_c}{H}\frac{dV}{d\phi}$$

$P_c(\phi,t)$: **probability distribution of** ϕ

- **Massless scalar, the field undergoes random walks**

$$\phi_0 \equiv \sqrt{\langle \phi^2 \rangle} \simeq \frac{H_I^{3/2}}{2\pi}\sqrt{t} = \frac{H_I}{2\pi}\sqrt{N}, \qquad N\textbf{: number of e-folds}$$

- **Massive case** $V(\phi) = \frac{1}{2}m^2\phi^2$**:**

$$\phi_0 \simeq \sqrt{\frac{3}{8\pi^2}\frac{H_I^2}{m}}$$

- **For** $V(\phi) = \frac{\lambda}{4}\phi^4$**:** $\qquad \phi_0 \simeq 0.36 H_I/\lambda^{1/4}$
- **In general,** $\qquad \boxed{V(\phi_0) \sim H_I^4}$

LARGE HIGGS VEV DURING INFLATION

- **Higgs has a shallow potential at large scale (small λ).**
- **Large Higgs vacuum expectation value (VEV) during inflation.**
- **For inflationary scale $\Lambda_I = 10^{16}$ GeV, the Hubble rate $H_I = \frac{\Lambda_I^2}{\sqrt{3}M_{pl}} \sim 10^{13}$ GeV, and $\lambda \sim 0.01$, the Higgs VEV after inflation is**

$$\phi_0 \simeq 0.36 H_I/\lambda^{1/4} \sim 10^{13} \text{GeV}.$$

- **For such a large VEV, the Higgs field can be sensitive to higher dimensional operators.**

HIGGS FIELD RELAXATION

POST-INFLATIONARY HIGGS RELAXATION

- As the inflation end, the H drops.
- When $H < m_{\phi,\mathrm{eff}}$, the Higgs field can relax classically

$$\ddot{\phi}(t) + 3H(t)\dot{\phi}(t) + \frac{\partial V_{\mathrm{eff}}\big(\phi, T(t)\big)}{\partial \phi} = 0$$

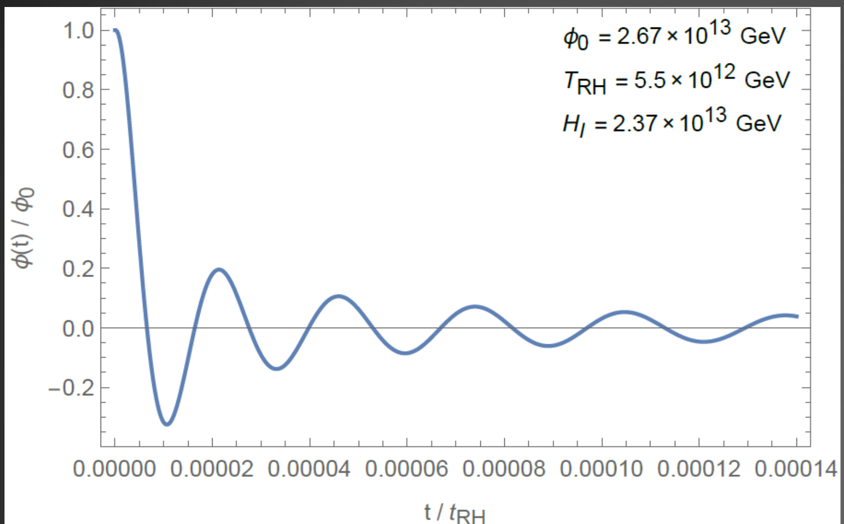
- $V_{\mathrm{eff}}(\phi, T)$ is the finite temperature effective potential.
- Higgs field oscillates with decreasing amplitude due to the Hubble friction.
- Relaxation time

$t_{rlx} = t_{RH}\left(\frac{2.532}{a_T T_{RH} t_{RH}}\right)^{4/3}$ if thermal mass dominates $V \approx \frac{1}{2}\alpha_T^2 T^2 \phi^2$

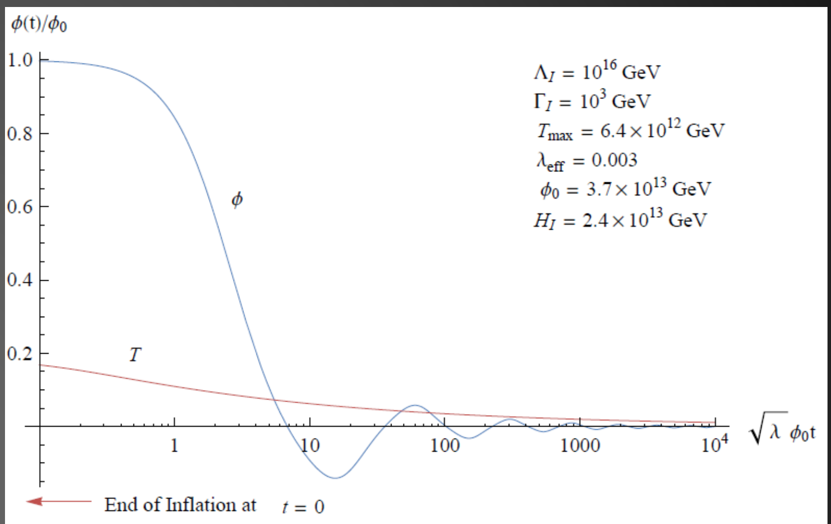
$t_{rlx} = 6.90/\sqrt{\lambda}\phi_0$ if the zero T dominates $V \approx \lambda\phi^4/4$

- Typically during reheating or right after reheating.

POST-INFLATIONARY HIGGS RELAXATION



Thermal mass dominated



Zero T potential dominated

- **What can this do for us?**
- **Breaks time reversal symmetry,**
  and provides the out of thermal equilibrium condition.
- **An important epoch for the matter-antimatter asymmetry!**

POST-INFLATIONARY HIGGS RELAXATION

- **If the thermal mass dominates,**

$$V(\phi, T) \approx \frac{1}{2}\alpha_T^2 T^2 \phi^2$$

where $\alpha_T \approx \sqrt{\left(\lambda + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 3y_t^2\right)/12} \approx 0.33$ **at** $\mu = 10^{13}$ **GeV.**

- **The equation of motion is approximately**

$$\ddot{\phi}(t) + \frac{2}{t}\dot{\phi}(t) + \alpha_T^2 \frac{T_{RH}^2\sqrt{t_{RH}}}{\sqrt{t}}\phi(t) = 0$$

- **A solution:**

$$\phi(t) = \phi_0 \left(\frac{3}{2}\right)^{2/3} \Gamma\left(\frac{5}{3}\right) J_{2/3}\left(\frac{4\alpha_T\beta}{3}x^{3/4}\right)\frac{1}{(\alpha_T\beta)^{2/3}\sqrt{x}}$$

where $\beta = T_{RH}t_{RH}$ **and** $x = t/t_{RH}$**.**

LEPTOGENESIS VIA THE RELAXATION OF THE HIGGS FIELD

SAKHAROV CONDITIONS

Andrei D. Sakharov (1967)

Successfully Leptogenesis requires:

1. **Deviation from thermal equilibrium**
   - Post-inflationary Higgs relaxation
2. **C and CP violations**
   - CP phase in the quark sector (not enough), higher dimensional operator, …
3. **Lepton number violation**
   - Right-handed Majorana neutrino, others …

EFFECTIVE OPERATOR

M. E. Shaposhnikov (1987),
M. E. Shaposhnikov (1988)

- **Consider the effective operator:**

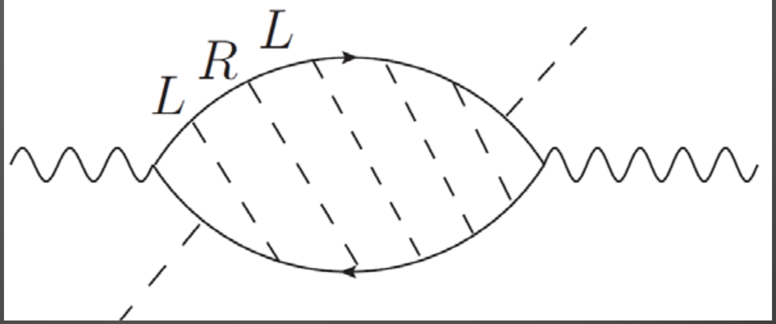
$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right),$$

W and B: $SU(2)_L$ and $U(1)_Y$ gauge fields

$\widetilde{W}$: dual tensor of W

Λ_n: energy scale when the operator is relevant

- **In standard model, integrating out a loop with all 6 quarks:**

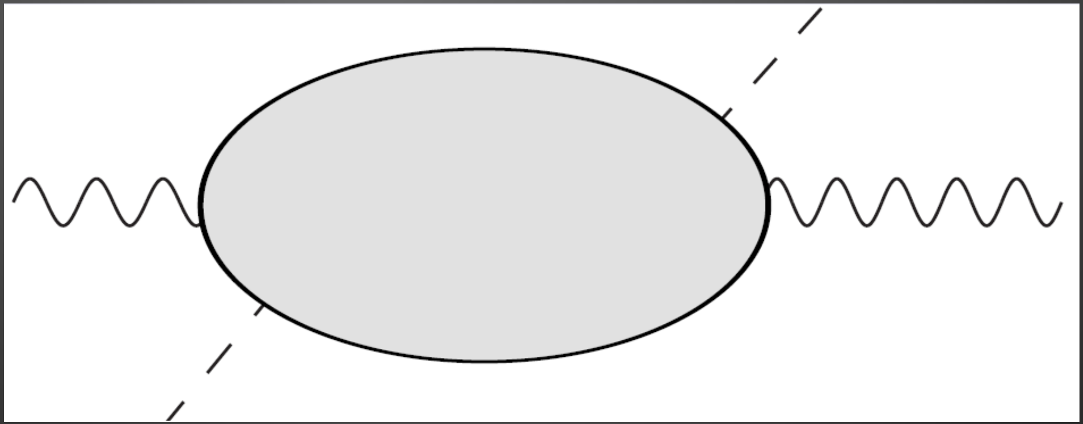


- **But suppressed by small Yukawa and small CP phase**

EFFECTIVE OPERATOR

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right)$$

- Replace the SM fermions by heavy states that carry $SU(2)$ charge.
- Scale: $\Lambda_n = M_n$ mass (must not from the SM Higgs) or
  $\Lambda_n = T$ temperature



EFFECTIVE CHEMICAL POTENTIAL

Dine et. al. (1991)
Cohen, Kaplan, Nelson (1991)

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}\phi^2\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right)$$

- **Using electroweak anomaly equation, we have**

$$\mathcal{O}_6 = -\frac{1}{\Lambda_n^2}|\phi|^2\partial_\mu j^\mu_{B+L},$$

where j^μ_{B+L} is the $B+L$ fermion current.

- **Integration by part:**

$$\mathcal{O}_6 = \frac{1}{\Lambda_n^2}\left(\partial_\mu|\phi|^2\right)j^\mu_{B+L}$$

- **Similar to the one use by spontaneous baryogenesis.**
- **Breaks CPT spontaneously while ϕ is changing!**
- **Sakharov conditions doesn't have to be satisfied explicitly in this form.**

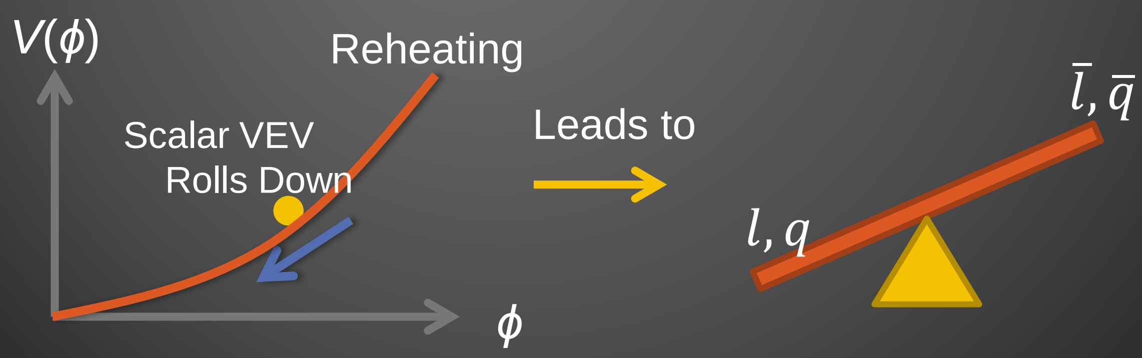
EFFECTIVE CHEMICAL POTENTIAL

$$\mathcal{O}_6 = \frac{1}{\Lambda_n^2}(\partial_\mu|\phi|^2)j^\mu_{B+L}$$

- **Effective chemical potential** for baryon and lepton number:

$$\mu_{\text{eff}} = \frac{1}{\Lambda_n^2}\partial_t|\phi|^2$$

- **Shifts the energy levels** between fermions and anti-fermions while Higgs is rolling down ($\dot{\phi} \neq 0$).



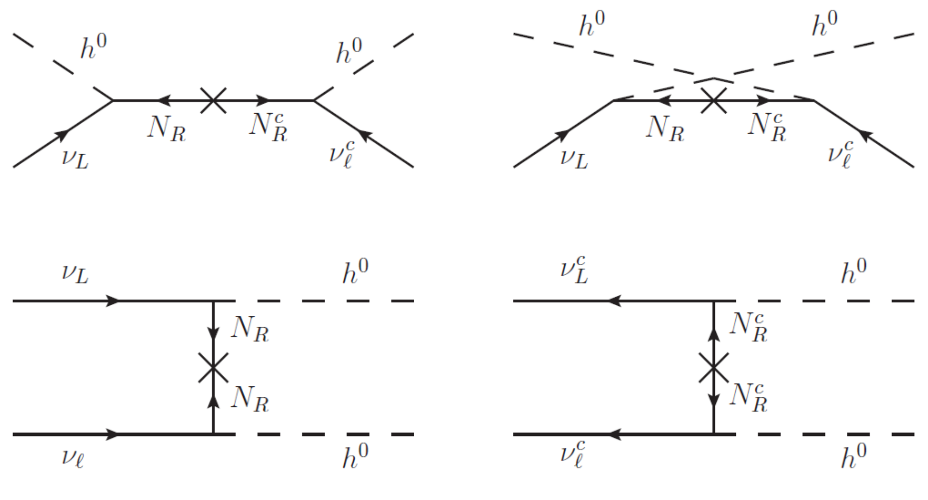
LEPTON NUMBER VIOLATION

Last ingredient:

- **Right-handed neutrino N_R with Majorana mass term M_R.**

The processes for $\Delta L = 2$:

- $\nu_L h^0 \leftrightarrow \overline{\nu_L} h^0$
- $\nu_L \nu_L \leftrightarrow h^0 h^0$
- $\overline{\nu_L \nu_L} \leftrightarrow h^0 h^0$



For $m_\nu \sim 0.1$ eV,

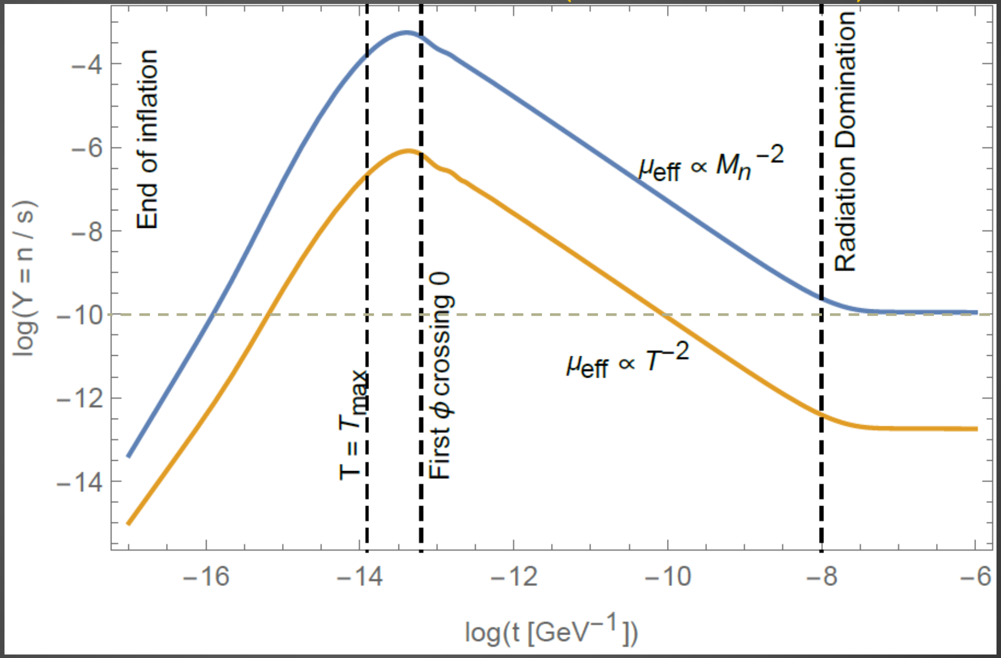
$$\sigma_R \sim \frac{\Sigma_i m_{\nu,i}^2}{16\pi v_{EW}^2} \sim 10^{-31}\ \mathrm{GeV}^{-2}.$$

EVOLUTION OF LEPTON ASYMMETRY

LY, Pearce, Kusenko
Phys. Rev. D92 (2015)

Boltzman equation:

$$\dot{n}_L + 3Hn_L \approx -\frac{2}{\pi^2}T^3\sigma_R\left(n_L - \frac{2}{\pi^2}\mu_{eff}T^2\right)$$



$\Lambda_I = 1.5 \times 10^{16}$ **GeV,** $\Gamma_I = 10^8$ **GeV,** $T_{RH} = 5 \times 10^{12}$ **GeV, and** $\phi_0 = 6 \times 10^{13}$ **GeV.**
For $\mu_{\text{eff}} \propto M_n^{-2}$ **case, choose** $M_n = 5 \times 10^{12}$ **GeV.**

Could be the origin of matter-antimatter asymmetry!

SUMMARY

- **Our universe seems to be right on the meta-stable region.**
- **The quartic coupling of the Higgs potential turns negative giving a shallow potential.**
- **Higgs can obtain large vacuum expectation during inflation.**
- **The relaxation of the Higgs VEV happens during reheating.**
- **Higgs relaxation provides the out of thermal equilibrium condition and breaks T invariant.**
- **Leptogenesis via the Higgs relaxation is possible.**
- **Higgs relaxation is an important epoch in the early universe.**

Thanks for your listening!