

Ending inflation with a bang: Higgs vacuum metastability in $R + R^2$ gravity

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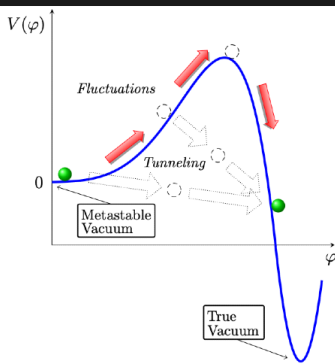
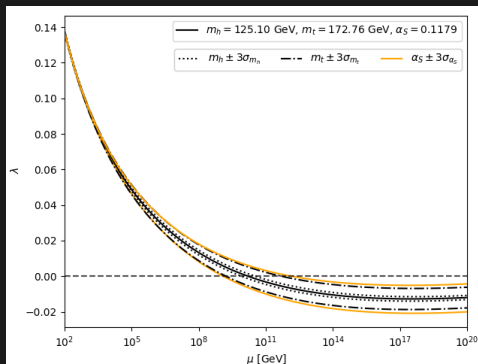
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The EW vacuum metastability

Experimental values of SM particle masses m_h, m_t indicate that:

- SM may be valid up to μ_{QG} ; early Universe consistent minimal model.
- currently in metastable EW vacuum \rightarrow constrain fundamental physics.

$$V_H(h, \mu, R) = \frac{\xi(\mu)}{2} R h^2 + \frac{\lambda(\mu)}{4} h^4$$



Bubble nucleation from vacuum decay

- Decay expands at c with singularity within \rightarrow true vacuum bubbles:

$$d\langle\mathcal{N}\rangle = \Gamma d\mathcal{V} \Rightarrow \langle\mathcal{N}\rangle = \int_{\text{past}} d^4x \sqrt{-g} \Gamma(x)$$

- Universe still in metastable vacuum \rightarrow no bubbles in past light-cone:

$$P(\mathcal{N} = 0) \propto e^{-\langle\mathcal{N}\rangle} \sim \mathcal{O}(1) \Rightarrow \langle\mathcal{N}\rangle \lesssim 1$$

- Low decay rate Γ today, but higher rates in the early Universe.

Vacuum bubbles expectation value (during inflation)

$$\langle\mathcal{N}\rangle = \frac{4\pi}{3} \int_0^{N_{\text{start}}} dN \left(\frac{a_{\text{inf}} (\eta_0 - \eta(N))}{e^N} \right)^3 \frac{\Gamma(N)}{H(N)} \leq 1$$

Decay rate from Hawking-Moss instanton

- Classical solutions to the tunneling process from false to true vacuum.
- High H 's during inflation, CdL \rightarrow HM instanton with action difference

$$B_{\text{HM}}(R) \approx \frac{384\pi^2 \Delta V_{\text{H}}}{R^2}$$

where $\Delta V_{\text{H}} = V_{\text{H}}(h_{\text{bar}}) - V_{\text{H}}(h_{\text{fv}})$: barrier height \rightarrow decay rate

$$\Gamma_{\text{HM}}(R) \approx \left(\frac{R}{12}\right)^2 e^{-B_{\text{HM}}(R)}$$

- Curvature effects enter at tree level via non-minimal coupling ξ :

$$V_{\text{H}}(h, \mu, R) = \frac{\xi(\mu)}{2} R h^2 + \frac{\lambda(\mu)}{4} h^4$$

Higgs potential in curved space-time

- Minkowski terms to 3-loops, curvature corrections in dS at 1-loop:

$$V_{\text{H}}(h, \mu, R) = V_{\Lambda} - \kappa R - \frac{m^2}{2}h^2 + \frac{\xi}{2}Rh^2 + \frac{\lambda}{4}h^4 + \frac{\alpha}{144}R^2 + \Delta V_{\text{loops}},$$

where the loop contribution can be parametrized as

$$\Delta V_{\text{loops}} = \frac{1}{64\pi^2} \sum_{i=1}^{31} \left\{ n_i \mathcal{M}_i^4 \left[\log \left(\frac{|\mathcal{M}_i^2|}{\mu^2} \right) - d_i \right] + \frac{n'_i R^2}{144} \log \left(\frac{|\mathcal{M}_i^2|}{\mu^2} \right) \right\}$$

- RGI: choose $\mu = \mu_*(h, R)$ such that $\Delta V_{\text{loops}}(h, \mu_*, R) = 0 \rightarrow$

RGI effective Higgs potential

$$V_{\text{H}}^{\text{RGI}}(h, R) = \frac{\xi(\mu_*(h, R))}{2} Rh^2 + \frac{\lambda(\mu_*(h, R))}{4} h^4 + \frac{\alpha(\mu_*(h, R))}{144} R^2$$

Overview of computation

- 1 Calculate ΔV_H and plug it in $\Gamma \approx \left(\frac{R}{12}\right)^2 e^{-\frac{384\pi^2 \Delta V_H}{R^2}}$.
- 2 Cosmological quantities according to the inflationary model $V_I(\tilde{\phi})$.
- 3 Complete calculation of $\langle \mathcal{N} \rangle$ imposing the condition $\langle \mathcal{N} \rangle \leq 1$.

$$\langle \mathcal{N} \rangle = \frac{4\pi}{3} \int_0^{N_{\text{start}}} dN \left(\frac{a_{\text{inf}} (\eta_0 - \eta(N))}{e^N} \right)^3 \frac{\Gamma(N)}{H(N)} \leq 1$$

- 4 Result: constraints on $\xi \geq \xi_{\langle \mathcal{N} \rangle=1}$ and cosmological implications from the time of predominant bubble nucleation.

RGI effective Higgs potential in $R + R^2$ gravity

$$S = \int d^4x \sqrt{-g_J} \left[\frac{M_P^2}{2} \left(1 - \frac{\xi h^2}{M_P^2} \right) R_J + \frac{1}{12M^2} R_J^2 + \frac{1}{2} g_J^{\mu\nu} \partial_\mu h \partial_\nu h - \frac{\lambda}{4} h^4 \right]$$

$$\Rightarrow \dots \Rightarrow \mathcal{L} \approx \frac{M_P^2}{2} R + \frac{1}{2} \partial_\mu \tilde{\phi} \partial^\mu \tilde{\phi} + \frac{1}{2} \partial_{\mu\rho} \partial^\mu \rho - U(\tilde{\phi}, \rho),$$

$$U(\tilde{\phi}, \rho) = V_1(\tilde{\phi}) + m_{\text{eff}}^2(\tilde{\phi}, \mu_*) \frac{\rho^2}{2} + \lambda_{\text{eff}}(\tilde{\phi}, \mu_*) \frac{\rho^4}{4} + \frac{\alpha(\mu_*)}{144} R^2(\tilde{\phi}) + \mathcal{O}\left(\frac{\rho^6}{M_P^2}\right),$$

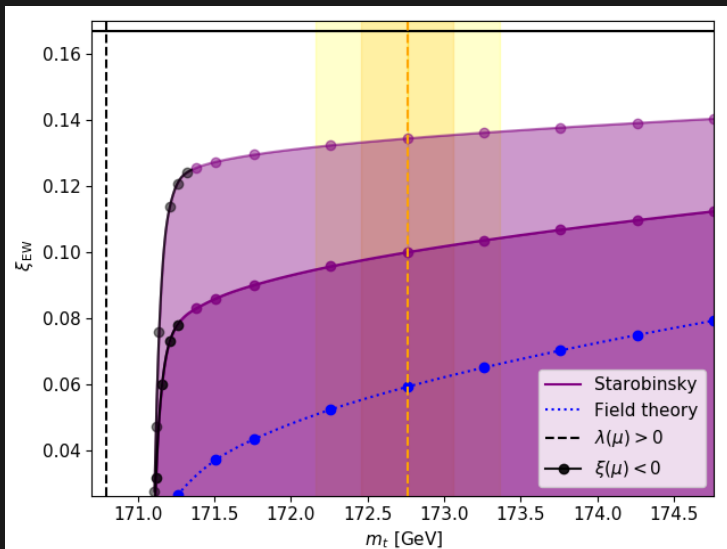
where $\Xi(\mu_*) = \xi(\mu_*) - \frac{1}{6}$ and

$$V_1(\tilde{\phi}) = \frac{3M^2 M_P^4}{4} \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\tilde{\phi}}{M_P}} \right)^2,$$

$$m_{\text{eff}}^2 = \xi R + 3M^2 M_P^2 \Xi \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\tilde{\phi}}{M_P}} \right) e^{-\sqrt{\frac{2}{3}} \frac{\tilde{\phi}}{M_P}} + \frac{\Xi}{M_P^2} \partial_\mu \tilde{\phi} \partial^\mu \tilde{\phi},$$

$$\lambda_{\text{eff}} = \lambda + 3M^2 \Xi^2 e^{-2\sqrt{\frac{2}{3}} \frac{\tilde{\phi}}{M_P}} + \frac{4 [\xi R + \Delta m_1^2] \Xi^2}{M_P^2} + \frac{4\Xi^3}{M_P^4} \partial_\mu \tilde{\phi} \partial^\mu \tilde{\phi}.$$

Results: Lower ξ -bounds for varying top quark mass



Conclusions

- Consistent inclusion of 1-loop curvature corrections beyond dS in $R + R^2$ gravity \rightarrow stricter ξ -bounds from extra negative terms in V_H :

$$\xi_{\text{EW}} \gtrsim 0.1 > 0.06$$

- Bubble nucleation in the last moments of inflation: breakdown of dS approximations and necessity to consider the dynamics of reheating.
- Approaching the conformal point \Rightarrow HM validity questionable.
- Possibly hints against eternal inflation (again).