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

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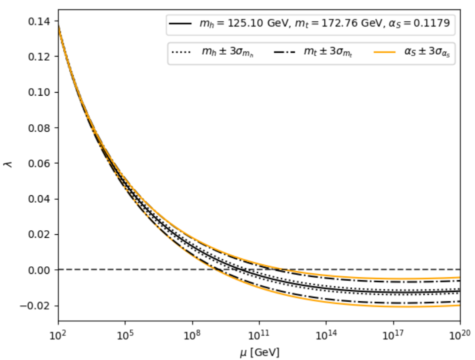
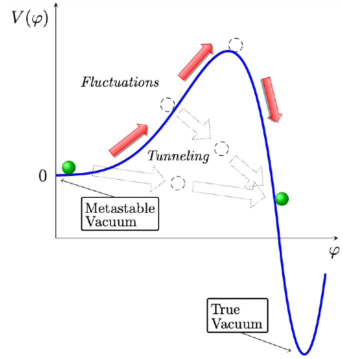
The EW vacuum metastability

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

- currently in metastable EW vacuum $\rightarrow$ constrain fundamental physics.

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





Markkanen *et al*, "Cosmological Aspects of Higgs Vacuum Metastability", 2018.

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:

$$\langle\mathcal{N}\rangle \lesssim 1$$

Vacuum bubbles expectation value (during inflation)

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

Overview of computation

1. Calculate $\Delta V_{\rm H}$ and plug it in $\Gamma \approx \left(\frac{R}{12}\right)^2 e^{-\frac{384\pi^2 \Delta V_{\rm H}}{R^2}}$.

2. Cosmological quantities according to the inflationary model $V_{\rm I}(\tilde{\phi})$; for Starobinsky/R^2 inflation $V_{\rm I}(\phi) = \frac{3M^2 M_P^4}{4}\left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\right)^2$.

3. Complete calculation of $\langle\mathcal{N}\rangle$ imposing the condition $\langle\mathcal{N}\rangle \leq 1$.

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

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

Higgs potential in curved spacetime

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

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

where the loop contribution can be parametrized as

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

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

RGI effective Higgs potential

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

Markkanen *et al*, "The 1-loop effective potential for the Standard Model in curved spacetime", 2018.

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

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

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

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

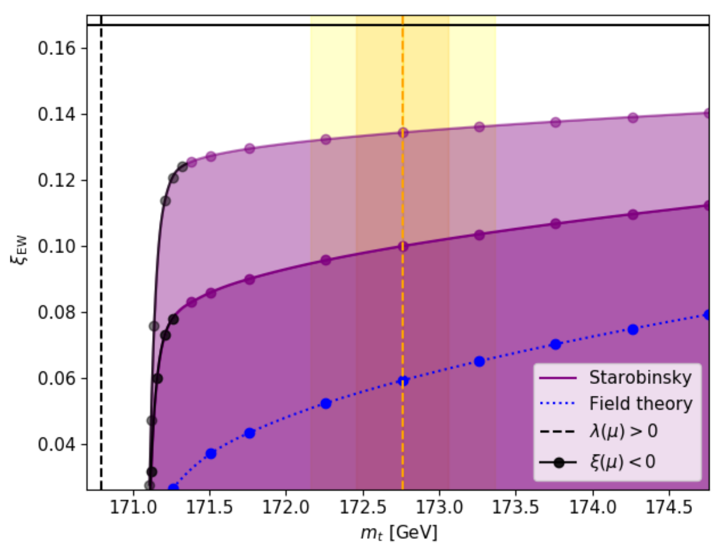
where $\Xi(\mu_*)=\xi(\mu_*)-\frac{1}{6}$ and

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

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

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

Results: Lower ξ-bounds for varying top quark mass



Conclusions

- Minimal model of the early universe: SM + Starobinsky inflation (observationally favoured) from modification of gravity $R + R^2$.

- Vacuum decay constraints on the Higgs-curvature coupling, with state-of-the-art $V_{\rm eff}^{\rm RGI}$ (3-loop couplings, 1-loop dS corrections):

$$\xi_{\rm EW} \gtrsim 0.1 > 0.06\,,$$

  give stricter ξ-bounds from extra negative terms in $V_{\rm H}^{\rm RGI}$.

- Bubble nucleation in the last moments of inflation: breakdown of dS approximations and necessity to consider the dynamics of reheating.

- Possibly hints against eternal inflation (again).