

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

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HEP2023 - 40th Conference on Recent Developments in High Energy Physics and Cosmology, Ioannina, Greece

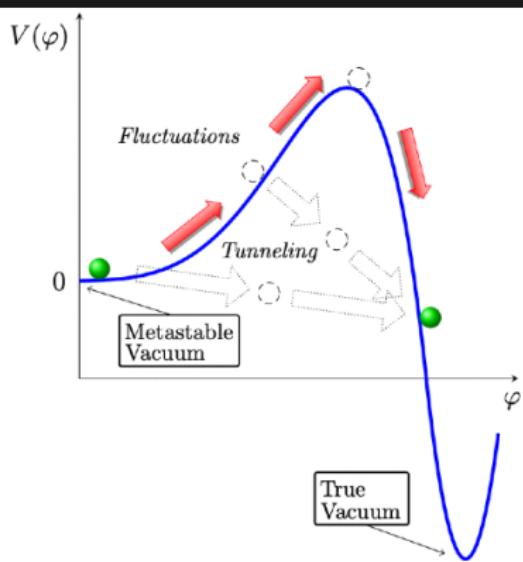
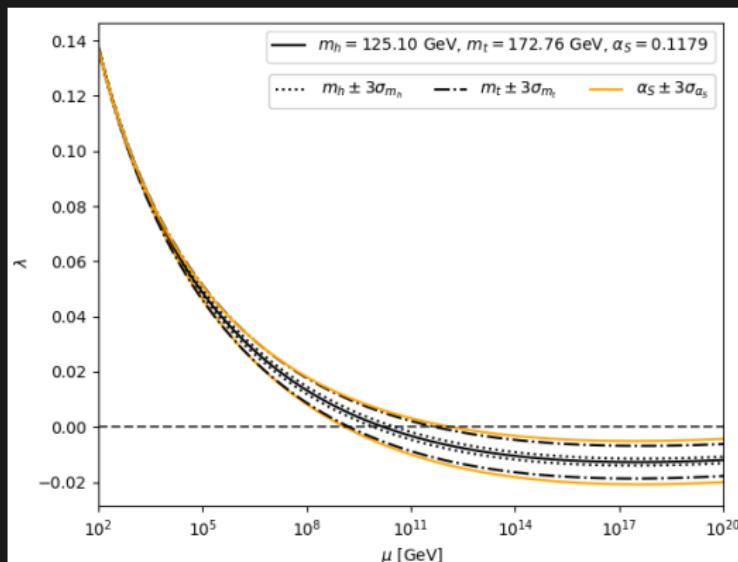
5 April 2023

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.

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



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:

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

Vacuum bubbles expectation value (during inflation)

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

Overview of calculation

Aims

- study the electroweak (EW) vacuum decay during inflation.
- constrain the Higgs-curvature coupling ξ in a “realistic” scenario.

Previous approaches

- dS spacetime where H is a constant free parameter.
- Tree-level effective Higgs potential (usually).
- Scale choices: $\mu = h$, $\mu^2 = ah^2 + bR^2$.

Improvements/differences

- Realistic inflationary model with $H(t)$ beyond slow-roll.
- RGI Higgs potential with 3-loop running in a curved background to 1-loop with additional terms from the conformal transformation.

Tetradis '23, Strumia and Tetradis '22, De Luca *et al* '22, Li *et al* '22, Cruz *et al* '22, Devoto *et al* '22, Vicentini '22, Figueroa *et al* '21, Lebedev '21, Kost *et al* '21, Li *et al* '21, Mantziriset *et al* '20, Rusak '20, Fumagalli *et al* '19, Salehian and Firouzjahi '19, Markkanen *et al* '18, Espinosa '18, Rajantie and Stoprya '17, Ema '17, ...

Higgs potential in curved spacetime

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

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

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

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

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

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

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

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

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

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

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

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

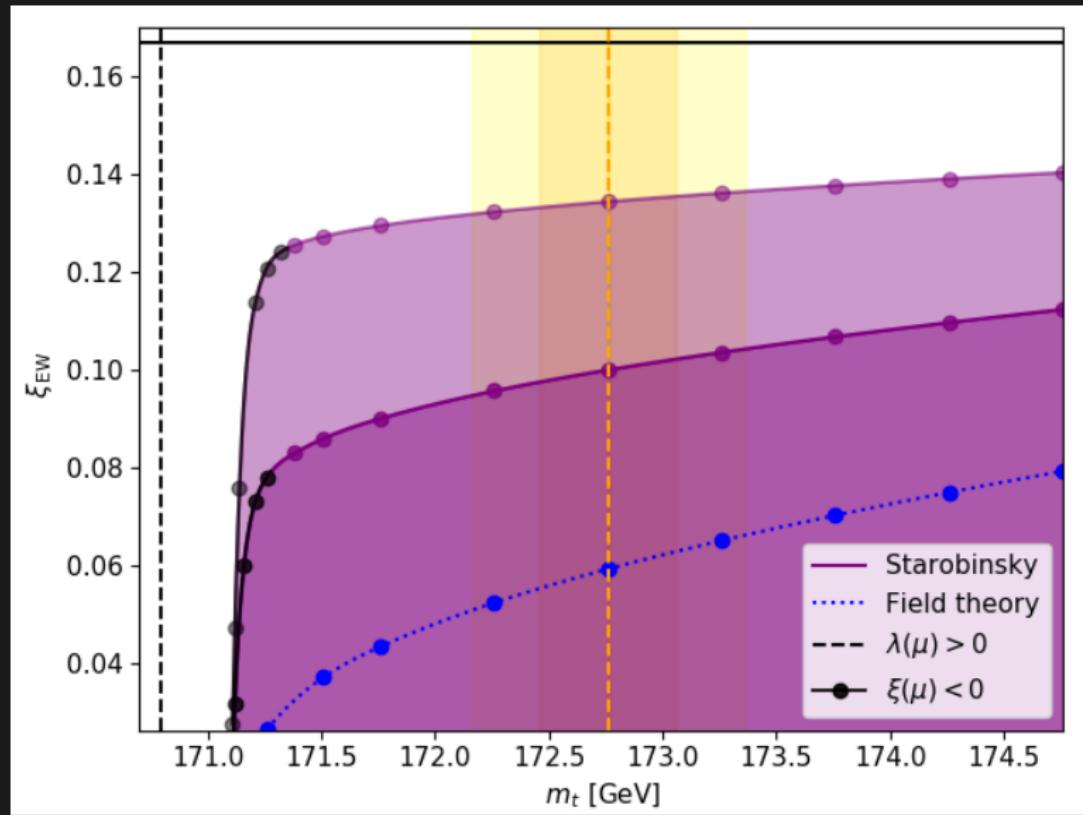
Overview of computation

- ① Calculate ΔV_H and plug it in $\Gamma_{\text{HM}} \approx \left(\frac{R}{12}\right)^2 e^{-\frac{384\pi^2 \Delta V_H}{R^2}}$.
- ② Cosmological quantities according to the inflationary model $V_I(\tilde{\phi})$; for Starobinsky/ R^2 inflation $V_I(\tilde{\phi}) = \frac{3M^2 M_P^4}{4} \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\tilde{\phi}}{M_P}}\right)^2$.
- ③ Complete calculation of $\langle \mathcal{N} \rangle$ imposing the condition $\langle \mathcal{N} \rangle \leq 1$.

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

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

Results: Lower ξ -bounds for varying top quark mass



Conclusions

- Minimal model of the early universe: general result of embedding and RG improving a scalar field (here SM Higgs) in Starobinsky inflation.
- Vacuum decay constraints on the Higgs-curvature coupling, with state-of-the-art $V_{\text{eff}}^{\text{RGI}}$ (3-loop couplings, 1-loop dS corrections):

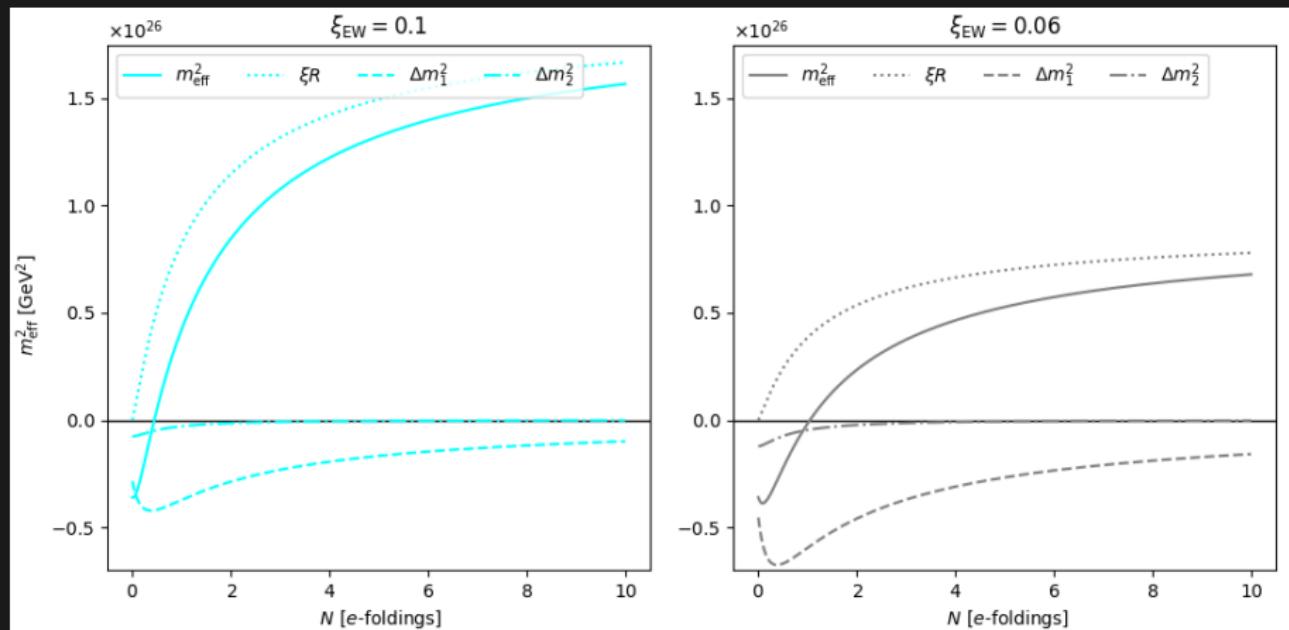
$$\xi_{\text{EW}} \gtrsim 0.1 > 0.06 ,$$

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

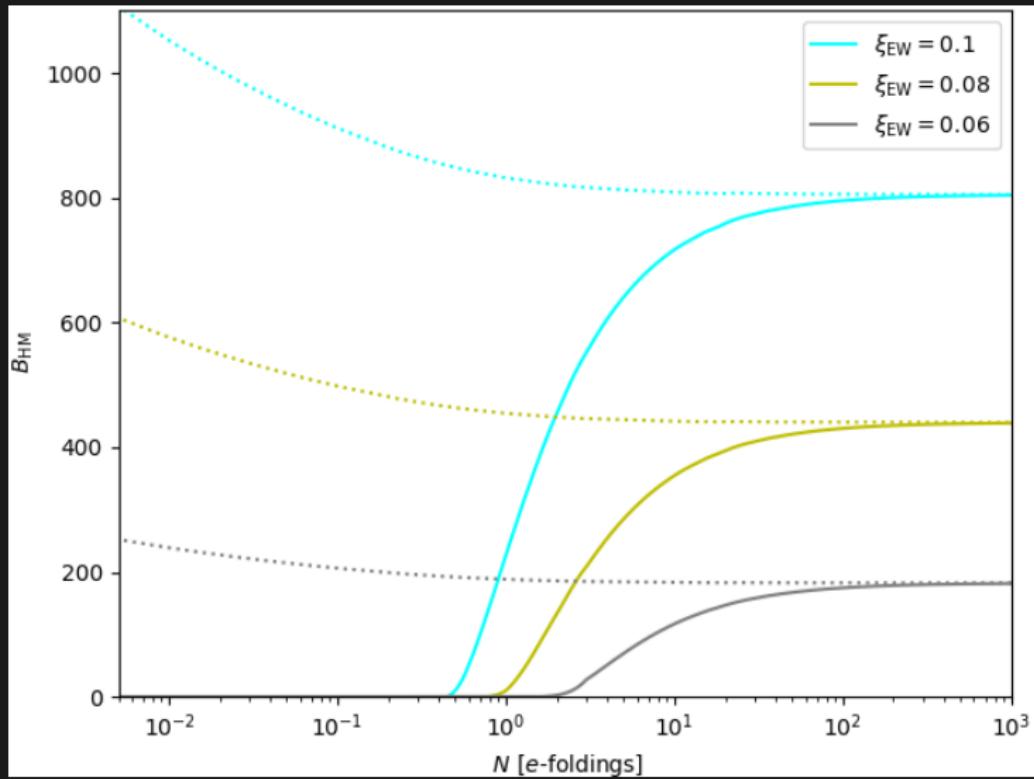
- Bubble nucleation in the last moments of inflation: breakdown of dS approximations and necessity to consider the dynamics of reheating.
- Possibly hints against eternal inflation.

Additional slides

Factors of the potential's quadratic term



HM bounce in Starobinsky Inflation and Field Theory



Numerical solution for vacuum decay during inflation

Solve the system of coupled differential equations beyond slow-roll:

$$\frac{d^2\phi}{dN^2} = \frac{V_I(\phi)}{M_P^2 H^2} \left(\frac{d\phi}{dN} - M_P^2 \frac{V'_I(\phi)}{V_I(\phi)} \right)$$

$$\frac{d\tilde{\eta}}{dN} = -\tilde{\eta}(N) - \frac{1}{a_{\text{inf}} H(N)}$$

$$\frac{d\langle \mathcal{N} \rangle}{dN} = \gamma(N) = \frac{4\pi}{3} \left[a_{\text{inf}} \left(\frac{3.21e^{-N}}{a_0 H_0} - \tilde{\eta}(N) \right) \right]^3 \frac{\Gamma(N)}{H(N)}$$

where $\tilde{\eta} = e^{-N} \eta$ with η : conformal time and

$$H^2 = \frac{V_I(\phi)}{3M_P^2} \left[1 - \frac{1}{6M_P^2} \left(\frac{d\phi}{dN} \right)^2 \right]^{-1},$$

$$R = 6 \left(\frac{\dot{a}^2}{a^2} + \frac{\ddot{a}}{a} \right) = 12H^2 \left[1 - \frac{1}{4M_P^2} \left(\frac{d\phi}{dN} \right)^2 \right].$$